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Lead Paint Removal by Confined Hydraulic Jet

SBIR Phase I Final Report

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A separate effects approach used small (14 × 14 cm), painted wood panels (pine, fir plywood, and oak) for studies over a range of hydrojet characteristics and operating parameters. The apparatus was assembled from standard commercial components. Tests were done at pressure levels from 500 to 1500 psi (3.5-10.5 MPa) using a 15-degree fan spray nozzle at nozzle-surface separations of 1 to 3 in. (2.5-7.6 cm). The dominant factor was the character of the wood with removal most on pine specimens and least on oak, greater with the grain than across the grain, and more in the soft wood than in the hard wood of the growth rings. Water and paint/wood debris were effectively contained and extracted from the work surface by the shroud.

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ABSTRACT

This Phase I feasibility study examined a confined hydraulic jet as means for stripping lead-based paint from wood surfaces without dispersing debris (paint chips and wood splinters) into the ambient. Laboratory tests verified the capability for removing and concentrating the hazardous lead component. However, paint removal was accompanied by gouging of the wood substrate. The technique can be applied for preparation of older wood buildings (military, inner-city) prior to demolition and cleanup of chemically contaminated building interior and exterior surfaces.

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FOREWORD

This research study fulfills the requirements of the Small Business Innovation Research (SBIR) award from the U. S. Department of the Army, Corps of Engineers, Construction Engineering Research Laboratories (USACERL) to the PAI Corporation under contract number USACERL DACA88-93-C-0003C. The USACERL technical monitor was Dr. Ashok Kumar.

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1 INTRODUCTION

This SBIR Phase I study responds to the request by the Construction Engineering Research Laboratory (CERL), U.S. Department of the Army, for development of an innovative technology for effective and low-cost removal of lead-based paint from painted surfaces in buildings scheduled for demolition. The paint is to be stripped without hazard to workers, occupants, or the environment.

Background

The U.S. Army estimates that it is custodian of over 1 billion square feet of buildings constructed prior to 1980 in which lead-based paints were used to cover building interior and exterior surfaces.[1] With much of this "acreage" being considered for demolition or conversion, disposal of lead-contaminated debris becomes a serious concern.

General demolition practice removes buildings and internal structures with the paint left *in situ* on the painted surfaces. Disposal of the resulting debris is by on-site burning (if combustible), in commercial or on-site landfills (dumps), or as construction fill where land is being prepared for other uses. However, the situation has now changed where materials hazardous to the bioenvironment (particularly man) are involved. Thus, federal environmental laws and regulations stipulate specific handling and disposal procedures (e.g., 40 CFR 261 ff. dealing with solid wastes) that severely complicate the issue. These laws and regulations impact equally the waste generator, the waste transporter, and the waste site operator. Hence, there is much incentive to utilize procedures that minimize the quantity of hazardous waste produced and to simplify its removal and disposal. Lead (as in paints) is one such hazardous material.

The Environmental Protection Agency (EPA) lists methods for the storage, treatment, and disposal of hazardous materials.[2] This listing is reproduced here as ***Table 1*** and, while directed to recordkeeping, is indicative of the extent of concern and the depth of approach to hazardous waste management. Note that stripping is one of the treatment techniques included (Item T64). Many of the processes listed are complex, time-consuming, and costly but must be pursued in order to render the materials non-hazardous to the bioenvironment through transformation and/or isolation and, ultimately, to comply with law and avoid costly monetary penalties. Limitations on storage volume and disposal cost place a premium on the reduction of hazardous waste to a minimum amount.

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[1]While federal law in 1977 banned the residential use of lead paints (i.e., paints containing lead oxide pigments and lead acetate driers) because of toxicity, all construction prior to 1980 is suspect; since on-hand supplies may have been used in non-critical (i.e., non-residential) applications on military bases until all were consumed.

Table 1. Hazardous Waste Treatment, Storage, and Disposal Methods as Identified by EPA (40 CFR 264, Appendix I, Table 2)

(Code numbers are for purposes of identification in recordkeeping)

1. **Storage**

S01	Container (barrel, drum, etc.)
S02	Tank
S03	Waste pile
S04	Surface impoundment
S05	Other (specify)

2. **Treatment**

(a) Thermal Treatment

T06	Liquid injection incinerator
T07	Rotary kiln incinerator
T08	Fluidized bed incinerator
T09	Multiple hearth incinerator
T10	Infrared furnace incinerator
T11	Molten salt destructor
T12	Pyrolysis
T13	Wet air oxidation
T14	Calcination
T15	Microwave discharge
T16	Cement kiln
T17	Lime kiln
T18	Other (specify)

(b) Chemical Treatment

T19	Absorption mound
T20	Absorption field
T21	Chemical fixation
T22	Chemical oxidation
T23	Chemical precipitation
T24	Chemical reduction
T25	Chlorination
T26	Chlorinolysis
T27	Cyanide destruction
T28	Degradation
T29	Detoxification
T30	Ion exchange
T31	Neutralization
T32	Ozonation
T33	Photolysis
T34	Other (specify)

(c) Physical Treatment

(1) Separation of components

T35	Centrifugation
T36	Clarification
T37	Coagulation
T38	Decanting
T39	Encapsulation
T40	Filtration
T41	Flocculation
T42	Flotation
T43	Foaming
T44	Sedimentation
T45	Thickening
T46	Ultrafiltration
T47	Other (specify)

(2) Removal of Specific Components

T48	Absorption-molecular sieve
T49	Activated carbon
T50	Blending
T51	Catalysis
T52	Crystallization
T53	Dialysis
T54	Distillation
T55	Electrodialysis
T56	Electrolysis
T57	Evaporation
T58	High gradient magnetic separation
T59	Leaching
T60	Liquid ion exchange
T61	Liquid-liquid extraction
T62	Reverse osmosis
T63	Solvent recovery
T64	Stripping
T65	Sand filter
T66	Other (specify)

(d) Biological Treatment

T67	Activated sludge
T68	Aerobic lagoon
T69	Aerobic tank
T70	Anaerobic lagoon
T71	Composting
T72	Septic tank
T73	Spray irrigation
T74	Thickening filter
T75	Tricking filter
T76	Waste stabilization pond
T77	Other (specify)
T78–79	(Reserved)

3. Disposal

D80	Underground injection
D81	Landfill
D82	Land treatment
D83	Ocean disposal
D84	Surface impoundment (to be closed as a landfill)
D85	Other (specify)

Lead Toxicity

A principal driver behind the ban on lead paint use was ingestion by very young children through sucking on painted surfaces.[3] Lead is a potent human toxin, creating health problems ranging from impaired mental capacity to severe liver and kidney damage (including carcinomas). In the very young developing brain, the impact can be devastating; Soviero[4] reports a California study that found that one in five preschool children has enough lead in his/her blood to impede learning abilities. In 1991, 1,281 lead-poisoned children were detected in Maryland (1,100 in pre-1950 housing in Baltimore).[5] While 1992 statistics are incomplete, increased screening and a federal decision to lower the exposure level at which children are considered harmed[6] suggests that the number may be twice as high as in 1991. It is reputed that the downfall of the Roman Empire is directly traceable to the lead pipes used in Roman water supply systems.

Regulatory Guidelines

U.S. environmental law places a significant onus on those generating, handling, and/or disposing of hazardous materials to "create and maintain conditions under which man and nature can exist in productive harmony and fulfill the social, economic, and other requirements of present and future generations of Americans."[7]

Under the Clean Air Act (CAA),[8] lead is listed as one of five pollutants given "priority" status.[9] While the primary source of lead in the atmosphere is recognized as being from automotive emissions and, to a lesser extent, from lead smelting, the act also controls the open burning of lead-contaminated waste.

The Clean Water Act (CWA)[10] lists lead among the 126 priority toxic pollutants and prohibits its discharge to water bodies. The "best available technology economically achievable" is to be used to

[3]Other sources were the release of lead into the atmosphere from antiknock agents in gasolines burned in internal combustion engines and lead pigments incorporated in dishware used in food preparation and/or consumption.

[4]M. M. Soviero, "Can Your House Make You Sick," Popular Science, Vol. 241, No. 1, p. 80 (July 1992).

[5]Timothy B. Wheeler, The Sun, Section B, Wednesday, October 6, 1993.

[6]The federal guideline for the allowable body burden of lead has now been halved to 10 μg/dl of blood.

[7]National Environmental Protection Act (NEPA) of 1970, Section 101.

[8]Public Law 91-604 (1970) with major amendments in 1977 and 1990; regulations are found in 40 CFR 1-199.

[9]Others are sulfur dioxide, nitrogen-oxygen compounds, ozone, and particulate matter (< 10 microns).

[10]Public Law 92-500 (1972) with major amendments in 1977 and 1987; regulations are given in 40 CFR 100-149 and 400-471.

achieve a water quality standard of $0.1 \times LC_{50}$ (concentration effecting 50% mortality). This proscribes the landfill disposal of lead-contaminated materials under circumstances where lead can leach into ground waters.

The Resource Conservation and Recovery Act (RCRA)[11] provides for "cradle to grave" hazardous waste management. Under RCRA, solid waste is any discarded material that is not excluded by 40 CFR 261.4(a). Thus exempted is slag from primary lead processing but not lead arising from any subsequent sources. RCRA is the regulatory guide for present and future wastes and is concerned with discharges into groundwater and some air emissions (e.g., from incinerators) and general waste management, including spills and solid waste. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), known as Superfund, deals with past waste management activities.

Further, the Occupational Safety and Health Act (OSHA) tightly defines the work environment and specifies exposure limits for workers from hazardous and toxic materials. This requires the use of respirators and other protective clothing in areas in which the worker could inhale/injest lead-containing materials.

In toto, current law says release of lead to the atmosphere or to water, directly or indirectly, is a threat to public health; and exposure of workers to high point-levels of the contaminant is not permitted.

Objectives

The overall objective of this study is to determine the feasibility for developing a hydrojet system to remove lead paint from building surfaces prior to structure demolition or renovation through addition of vinyl or aluminum siding. The system is to be economic in respect to both capital and operating costs.

The Phase I effort focuses on:

- review of existing procedures for paint removal, and identification of methods best suited to Army/CERL needs;
- survey of typical sites to determine range for such variables as substrate material, surface condition, and work area accessibility; and procurement of small samples for preliminary evaluation;
- selection of techniques for detailed examination, and development of preliminary equipment/process designs;
- identification of feasibility issues, and evaluation of probability for successful development;
- definition of device material and component requirements, identification of procurement sources, determination of equipment availability and cost, and preliminary evaluation of system capital and operating costs;
- Assembly of prototypical equipment components, and performance of limited tests; and
- Preparation of a test plan for a Phase II program.

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[11]Public Law 94-580 (1976) with reauthorization in 1980 and major amendments in 1981 and 1982; regulations regarding solid wastes are in 40 CFR 260-265.

A subsequent Phase II effort would develop solutions to the identified technical problems, construct a full-sized apparatus, and demonstrate performance in the field.

Approach

This study was accomplished through two tasks with the first, definition studies, guiding the second, scoping studies. The requirements of the program were discussed with independent painting contractors and commercial equipment suppliers to establish performance, cost, and availability parameters. Initial hardware concepts were translated into laboratory-scale components, whose characteristics were defined through separate-effects tests:

(1) Paint removal from standard test panels using commercial components (compressor, drive, wand, and nozzles) in an open-cycle mode (water and debris not collected);

(2) Extraction of water and debris from the working surface without significant loss of either material to the work ambient; and

(3) Separation of debris from the water carrier.

The test panels were examined by eye (both directly and by microscope) to determine the extent of paint removal for the specific test conditions imposed, and results were photographically recorded. Conclusions on technique feasibility and recommendations on further development (Phase II) were derived from the test results.

Mode of Technology Transfer

This is an SBIR Phase I study to establish concept feasibility and, as such, is not at a technology transfer stage. However, it would be appropriate that military base personnel responsible for demolition of surplus buildings be kept informed about the development of this technique. Subsequently, notification to contractors could be handled by including a description of the technique in the Request for Purchase issued by the awarding agency.

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2 DEFINITION STUDIES (TASK 1)

Objectives

The objectives of Task 1 were as follows:

(1) Identify existing techniques for paint removal (commercial and proposed); and evaluate these means relative to Army/CERL needs for building demolition.

(2) Identify prototypical site(s); and characterize site(s) as to paint substrate material(s), surface conditions, and work area accessibility.

(3) Identify hydraulic jet paint removal system design and performance goals, define process elements, and prepare layout drawings.

(4) Identify waste format, and examine waste disposal requirements.

(5) Identify operating and capital costs.

Existing Paint Stripping Techniques (Subtask 1.1)

The federal government and U.S. industry have shared a significant interest in paint stripping with heavy emphasis being on aerospace and marine applications. This is evidenced by the 1993 Department of Defense/Industry Advanced Coatings Removal Conference;[12] which is the 6th in the series, heard 32 papers read, and was attended by over 280 participants. The automotive industry also has substantial interest in stripping of car bodies prior to repainting.

Where the coating substrate is a hard (e.g., metallic) material, impact of a mechanical removal agent (e.g., gas, water, ice, or plastic media jets) on the surface leaves the substrate unaffected. This is not the case where the substrate is a soft, fibrous material such as wood. Here, removal of the paint film bares the surface to direct attack by the stripping agent with consequent serious surface damage. If the desired result—as in this study—is to remove a coating containing toxic or otherwise hazardous constituents from wood intended for disposal (as in building demolition), damage to the wood surface is not an important factor. However, if the ability to repaint is controlling, paint film removal techniques must leave the surface in such condition that only minor "repairs" are needed. Painting contractors (see further discussion below) indicate that efficient and cheap means for paint removal from wood, by other than chemical means, is much desired.

Technology Review

Higgins[13] describes current paint stripping processes (principally for aircraft metal, graphite, and/or fiberglass surfaces) and handling of the resulting wastes. The waste materials consist of (1) solvent and paint residues and (2) wash water that contains both solids and dissolved chemicals. The

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[12] "Proceedings of the 1993 DOD/Industry Advanced Coating Conference," Gene Bishop, Ed., Hotel Westcourt, Phoenix, Arizona, May 25-27, 1993, undocumented.

[13] T. Higgins, "Hazardous Waste Minimization Handbook," Lewis Publishers, Chelsea, MI (1989): Chapter 7, "Removal of Paint and Coatings," pp 133-152.

most common procedure has been the physical application of a solvent to soften or debond the paint film, followed by pressurized water wash or scraping to remove the paint/solvent residue from the surface. Sand, abrasive, or glass bead blasting are also frequently used; though there has been concern about surface damage to the substrate material. Various means have been proposed to collect the waste and minimize its handling; disposal is through packaging and shipment to a licensed hazardous waste disposal site. A major concern exists under OSHA and NEPA regulations regarding release of volatile organic compounds (VOCs) into the work space and general atmosphere in the solvent process.

Modification of common practice has emphasized means for reducing the high volume of waste water. Not surprisingly, many alternatives to conventional techniques have also been proposed. Higgins lists these as encompassing:

- plastic media blasting (PMB)
- laser stripping
- waterjet stripping
- burn-off systems
- cryogenic stripping
- wet media stripping
- flashlamp stripping
- salt-bath stripping
- hot caustic stripping

He devotes much attention to the PMB technique. Along the way, it is noted that, despite the advantages of many of the new methods, there remain health and safety concerns and unanswered feasibility questions.

The comments following summarize paint removal processes as means for reducing hazardous demolition waste rather than preparing surfaces/components for reuse:

Manual Methods. Mechanical scraping, with or without film softening (blowtorch), remains the primary technique for removing paint from surfaces in residential and commercial buildings. Under some circumstances, as in industrial environments, power-tool sanding or sand-blasting may be an appropriate procedure. The material removed from the surface generally settles to the floor close by the work site, if in relatively large flakes, or is airborne and accumulates more widely on all surfaces in the work space. In all cases, the area must be swept or vacuumed to concentrate the waste; and the probability of leaving significant amounts uncollected is high. Further, the potential for personnel exposure during the removal operations is also high, despite protective equipment requirements, due to the long-term presence in the air of very fine dusts.

Chemical Methods. An alternative procedure involves chemical removal. Dumond Chemicals[14] produces a product under the trade designation Peel-Away I that they claim can be used to remove oil or latex lead-containing paint films up to 30 layers thick. This is a caustic mixture of calcium, magnesium, and sodium hydroxides that is coated on the surface, chemically reacts with the paint film, is absorbed into a backing material, and removed for disposal. It is a white paste without odor that can cause severe burns to external and internal tissues. Use of gloves (polyethylene, neoprene, or rubber) and eye goggles is recommended. Clean water should be kept close by for washing skin or irrigating eyes. Disposal of the waste must take into account that the stripping material is both chemically hazardous and toxic.

Other products under the Peel-Away label are designed for removal of elastomeric, acrylic, etc. paints from other than wood surfaces. These may be acids or polychlorinated hydrocarbons and are said

[14]U.S. Department of Labor, Material Safety Data Sheet, Peel-Away I, February 17, 1987; available through Dumond Chemicals Inc., 1501 Broadway, New York, NY, 10036, (212-840-2666), or from local paint suppliers.

to act by softening and crinkling the paint film at thicknesses up to seven layers. The paint is then removed by mechanical scraping. The presence in the work space of volatile, toxic organics complicates use of these materials. As with Peel-Away I, the waste product is hazardous and toxic beyond just the lead content.

Dumond Chemicals supplies these products to the Navy for building and ship paint removal in 55-gal drums.

Thermal Methods. As noted above, the use of a flame to soften the paint film and scraping to remove the film has long been the standard means for preparing surfaces for repainting. A modern-day technique replaces the torch with a laser that vaporizes the film (a pulsed CO_2 laser operates in the appropriate energy range). This is quick, clean, and efficient but puts lead vapors into the work atmosphere.

Given that the waste material is combustible, an incineration procedure could be considered. The debris would be processed through chippers and fed to a furnace. Absorber columns would remove lead and other hazardous contaminants from the stack gas. Nails, $CaSO_4$ (from wall board), film residues, etc. would be fused and appear as furnace slag. The heat produced could be used for on-site power supply. While this appears to be a feasible technique, it requires a fairly complex system and, to be economically effective, shipment of debris to a central site.

Non-thermal variants of the incineration process can be conceived in which the chipped material is chemically treated in a closed system to remove the paint film from the wood particles, separated by settling or filtration, treated as a slurry with lime and aluminum hydroxide, and set up as a cement in drums for ultimate disposal. Again, this is a complex process that is best accomplished by bringing debris to one or more fixed sites for treatment.

Current Practice

Painting contractors, equipment and paint supply businesses, and engineering research personnel were contacted to learn of their experience in paint removal. The information sought from these contacts were the technique(s) being used, experience with the particular equipment, efficacy in removing paint films, and operating costs (discussed in a following section). Some indicated that their "system" will not work on wood surfaces. While this review is not inclusive, it is believed to provide an indication of the current state-of-the-art.

Painting Contractors. Local (Knoxville, Tennessee area) Painting contractors were interviewed regarding their procedures:

- Brighter Concepts (Paul Sanford) does high-pressure water stripping on concrete and metal surfaces using a 15-deg, ceramic-tip, rotating nozzle. Operating pressures are in the 3000-4000 psi range. They have tried working on wood and report that it leaves the surface in a condition variously described as "fluffy" or "fuzzy." Repainting would require considerable sanding and/or buffing. Waste containment is by placing a simple plastic ground cover around the base of the structure and a screen at the cover drain. The collected materials (paint chips and wood splinters) are taken to a licensed hazardous waste disposal site; the waste water runs off onto the surrounding ground or into a storm sewer.

- Albert Bell does mostly sand blasting and some chemical removal on concrete and aluminum at commercial and industrial sites; the Tennessee Valley Authority (TVA) is a major client. He has stopped working with wood surfaces, mainly because of the restrictions relating to handling of lead-contaminated waste. Presumably, his open system does not meet the

compliance requirements imposed by TVA. He indicated that he would be very interested, if an effective technique for use with wood becomes available. He has used sodium carbonate powder in some applications.

- Tennessee Car Craft (Larry Burchett) uses a recyclable, plastic-granule medium for removing paint from auto parts and bodies prior to repainting. He says this is faster, cleaner, and cheaper than using solvents or other chemicals. Surcore Company of Denver, Colorado, sells and services the equipment used and trains operators.

<u>Paint Suppliers</u>. Contact with local purveyors of paint and painting supplies elicited the following information:

- Pittsburgh Paint Company markets a product made by Dumond Chemicals (New York, NY) under the trade name "Peel-Away" in about 6 formulations. The product consists of a fabric or paper backing strip on which reactive chemicals (e.g., caustics, methyl chloride) are coated. The strip is laid directly on the painted surface and left for an appropriate time. When lifted from the surface, the softened (liquified) paint film is also removed.

It is claimed that Peel-Away will remove paint films as much as 30 layers thick from wood surfaces in a single application. On cement, a Peel-Away variant deforms (crinkles) the paint film; the film can then be scraped off or removed by water jet.

The waste resulting from this treatment process consists of the paint removed, hazardous chemicals, backing strips, and wash waters. The latter may be required to remove traces of paint and reactive chemicals left on the surface. Users must exercise great care to avoid breathing the toxic vapors and contacting the skin with the hazardous chemicals during both the paint removal and waste handling phases of the operation.

- Sherwin-Williams Paint Company sells the Peel-Away product but notes that their "painters" prefer sandblasting when removing lead-paint coatings because of the "messiness" when dealing with hazardous chemicals. Sandblasting does require attention to the proper containment, collection, and disposal of the sand/paint waste mixture.

<u>Process Developers</u>. Several organizations developing paint stripping processes were contacted:

- Applied Radiological Control (Kennesaw, Georgia) offers a Crystalline Ice Blast (CIB) process for surface preparation, cleaning, and coating removal that uses ice chips carried in an air jet to remove the surface coating. It was originally developed for aircraft "depainting" but is also suggested as advantageous in other applications. Coating removal is said to be by generation and propagation of cracks rather than by abrasion. Once filtered, the now-melted water medium is drained away. The process produces 15-24 gal/h of waste water and claims a greater cost-efficiency than with other blast techniques.

- Oak Ridge National Laboratory (Oak Ridge, Tennessee) has described a technology proposed for removing vinyl and epoxy paints from the underwater hull portions of ships.[15] The system proposed uses (1) a shrouded rotating head with multiple waterjet nozzles supplied with fresh water at 35,000 psi and (2) a programmable controller for automated head operation. The

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[15] J. G. Arnold et al, "Design of an Ultra High Pressure Waterjet Paint Removal Tool for Ship Hulls," Oak Ridge National Laboratory (1988). Undocumented report submitted to David Taylor Research and Development Center through the U.S. Department of Energy.

intent was to design a system that was economically competitive with other paint removal systems and had reduced generation of waste. The design criteria included a paint removal rate of 15 m^2/hr with a paint chip and water capture rate of 95%. The waterjet system was found to have a substantial economic advantage over abrasive blasting.

- United Technologies Pratt and Whitney, Waterjet Systems, (Huntsville, Alabama) is developing high-pressure (up to 55,000 psi) waterjet systems for stripping coatings from aircraft fuselage and engines. A patented nozzle[16] overcomes the nonuniform force distribution associated with standard commercial nozzles (high near circumference, low near center) that is said to be the cause of nonuniform stripping and substrate damage. The rotating head has a number of offset nozzles.

  The Large Aircraft Robotic Paint Stripping (LARPS) embodiment of the Automated Robotic Maintenance System (ARMS) incorporates this flat force profile nozzle. A major goal of the ARMS/LARPS development is the nearly 100% reclamation of the process water. A system having 10 gal/min capacity has been demonstrated to produce high quality water, remove suspended solids down to 0.5-micron size, and increase nozzle and pump lifetime.

- Container Products Corporation (Wilmington, North Carolina) markets the KELLY decontamination system. This combines a high-pressure water spray with a vacuum recovery system and a rotary brush. The system is said to "totally control" the removal of paint from concrete floors. The brush materials available include nylon, stainless steel, and Scotch-Brite abrasives. A 3-M "Roto-Peen" system is needed for paint removal with the KELLY system.

Site Characterization (Subtask 1.2)

The objective of this subtask was to develop the requirements for field testing of the confined hydraulic technique for paint stripping from wood buildings at prototypical sites; thus:

(1) Characterize sites with respect to building parameters; namely, building type, paint substrate material, surface condition, etc.

(2) Determine operational requirements; namely, work area accessibility and restrictions, waste handling procedures, utilities availability, etc.

(3) Identify institutional issues pertinent to specific sites; namely, post regulations, labor sources, etc.

Since field testing, in the sense of demonstrating technique performance, was not within the scope of this Phase I effort, emphasis on this area was postponed to a proposed Phase II effort. However, limited information was obtained at a single Army base.

Fort Campbell, Kentucky. PAI Corporation has been involved for some time in air permitting compliance studies at Fort Campbell, Kentucky. In consequence, contact was established with the base's painting supervisor. Through discussion with him and by personal observation, some indication was obtained as to the scope of a "stripping job":

[16]S. A. Hofacker, "Aircraft Robotic Paint Stripping Using High Pressure Water," 8th Annual Hazardous Materials Management Conference, Phoenix, Arizona, October 28, 1993.

- Fort Campbell does have a number of structures with wood siding that were built about fifty years ago and probably painted with a lead-based paint. These buildings are not currently designated for paint stripping or demolition, and there has been no attempt to determine whether the paint is lead-based.

- The buildings have outside walls of vee-grooved, yellow pine siding.

- Large areas of the building's exterior surface were covered with flaking paint. These were large chips (see subsequent discussion in Chapter 3 under "Test Procedures (Subtask 2.3)", some fallen to the ground around the building and others only loosely adhering. Thus, mechanical scraping could remove much of the paint, leaving exposed bare-wood surface. Only an estimated 20% of the surface had tightly adhering paint.

- Microscopic examination of several paint chips from the site revealed four layers of paint had been applied over the building lifetime; the sample obtained had a paint film thickness of about 3/64 in. (see *Figure 18*).

An attempt was made to obtain a sample of the paint-adhering siding for examination in the PAI laboratory, but Fort Campbell staff would not permit off-base removal.

Oak Ridge, Tennessee. At both Department of Energy Oak Ridge plant sites and within the City of Oak Ridge itself, there are many wood-sided buildings dating from the 1943 period. However, a casual examination indicates that the exterior of most of these buildings has been upgraded by covering with aluminum or vinyl siding, thus making the painted surfaces inaccessible before demolition. Thus, special attention must be given to these buildings when they are razed; there is no indication of any near-term plans for taking down these structures. Phase II studies will attempt to locate an appropriate "shed" on one of the work sites.

Conceptual Design (Subtask 1.3)

Design Criteria

The following general criteria underlie the design of this proposed first-generation, shrouded, hydrojet paint removal system:

(1) Simple to avoid complications in component fabrication and procurement; this requires using standard nozzles, pumps, and separators.

(2) Portable to enable easy movement at the work site and between work sites; this dictates a wheeled or skid platform on which all system components are mounted.

(3) Sized to accommodate both building exterior and interior operations; this limits the dimensions and weights of the individual components.

(4) Lightweight to permit an individual operator to hold and move the stripping head on the work surface without undue fatigue; this requires support or counterweighting for the supply and exhaust hose extensions.

(5) Automated to provide rapid water cutoff when the head seal with the work surface is broken (to minimize water loss and spread of hazardous material in the work space); this requires rapid action as the head is lifted.

(6) Standardized through off-the-shelf components to reduce system costs and support convenient maintenance; this requires adaption of on-the-market equipment to the system needs.

Imposition of some of these criteria may result in a system whose performance is lower than can be attained with components specifically developed for the use. However, the gain in acceptance and utility may offset this deficiency.

System Layout

The system proposed to satisfy these criteria is shown in the schematic of *Figure 1*. The confined hydraulic jet design is conceived to reduce significantly the amount of waste water generated, to extract and concentrate the paint film residues, and to minimize introduction of lead paint or other hazardous constituents into the work space.

High-pressure water is supplied to the nozzle(s) positioned within the containment shroud (*Figure 2*) by a positive displacement pump. The interior of the shroud is kept at a slightly subatmospheric pressure by connection to the suction port of an exhaust blower to prevent loss of the water/debris mixture within the shroud to the work ambient. The suction line also serves as the conduit through which the waste (paint, wood, and water) is transferred to a centrifugal separator. The water underflow from the separator enters a settler/precipitator in which remaining debris "smalls" are gravity separated and dissolved lead can be precipitated by sodium bicarbonate addition. The water returns to the pump through a fines filter. Air taken overhead from the separator by the exhaust blower is discharged to the atmosphere through a micropore filter.

The pump is connected to the nozzle by flexible high-pressure hose; and the shroud to the separator, by a low-pressure flexible line. This allows for free movement of the shroud over the work surface. No pressure vessels are required by this layout; in the laboratory configuration, the prototype system can use modified stainless steel drums.

Operation of the paint stripping system is intended to be on a continuous basis. While a system can also be designed for the continuous removal of the waste products, this would add complexity. Intermittent waste recovery may be a better choice. It is to be noted that in both the separator and settler, density differences between wood splinter and isolated paint chips would effect separation in two zones. Removal of substrate wood is not a constraint in this application and should not affect system performance.

The shroud is "sealed" against the work surface by an elastomeric band wrapped around a notched polyvinyl chloride (PVC) ring (*Figure 3*). This allows ingress of ambient air, while preventing outward water flow. A moveable frame may be needed to support the weight of the shroud and its associated flexible piping connections; this support would minimize operator fatigue and, hence, enhance the production rate.

A semi-automated system is possible in which the shroud/nozzle is driven across the surface and indexed to the next elevation. Waterjet pressure and flow control is through a trigger-controlled valve in the laboratory operation; a pneumatic control could be used in a field system. A appropriate sensor would provide rapid water cutoff should the shroud be tipped far enough to open the surface seal.

Waste Collection/Disposal (Subtask 1.4)

The waste products generated by the hydraulic-jet stripping of paint from wood surfaces are the paint film, substrate wood, water, and filter materials. Since all of these waste products contain lead in

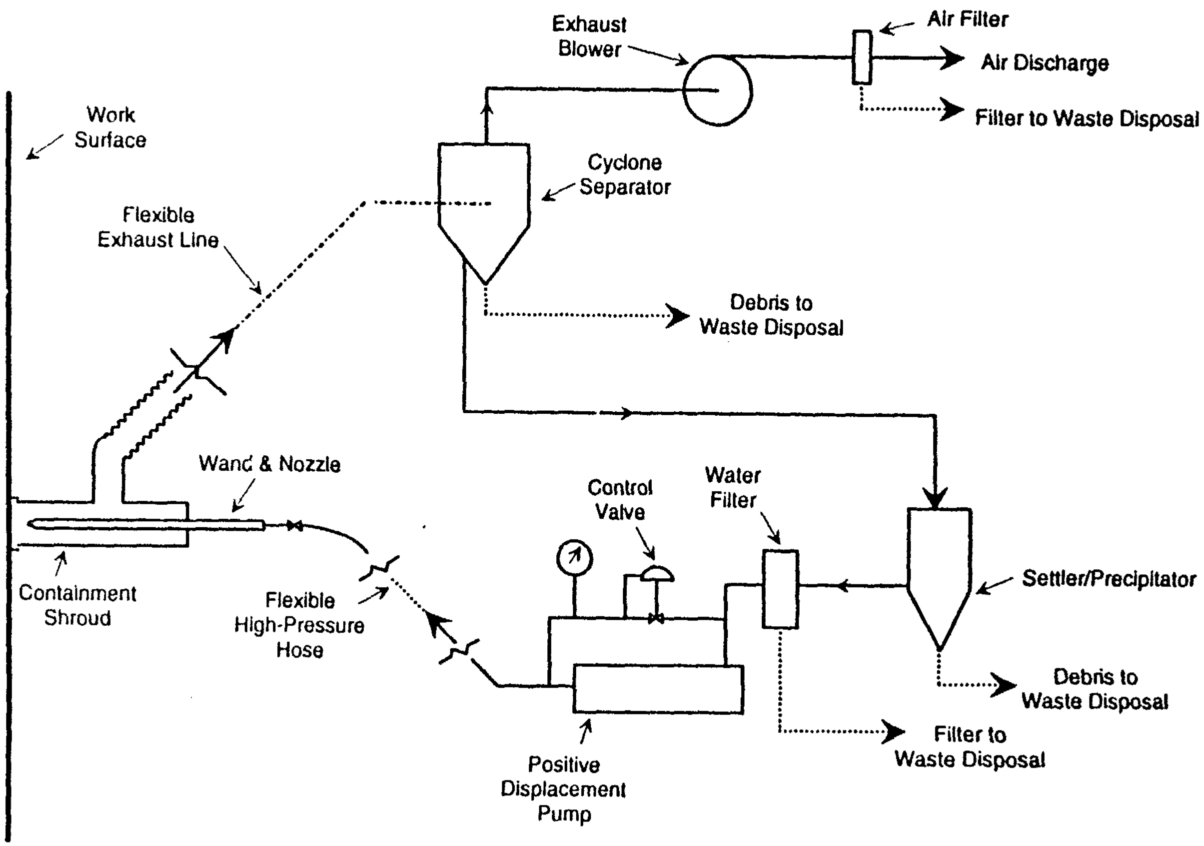

Figure 1. Schematic of Lead-Based Paint Removal System

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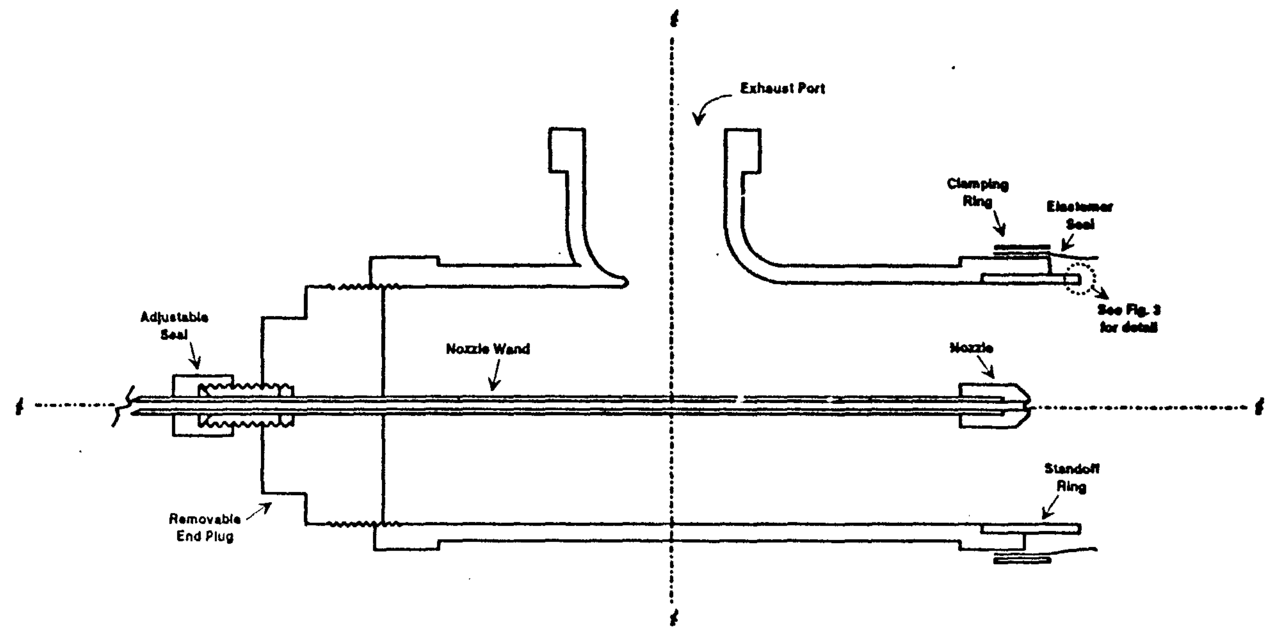

Figure 2. Schematic of Containment Shroud (PVC Tee) with Nozzle and Wand.

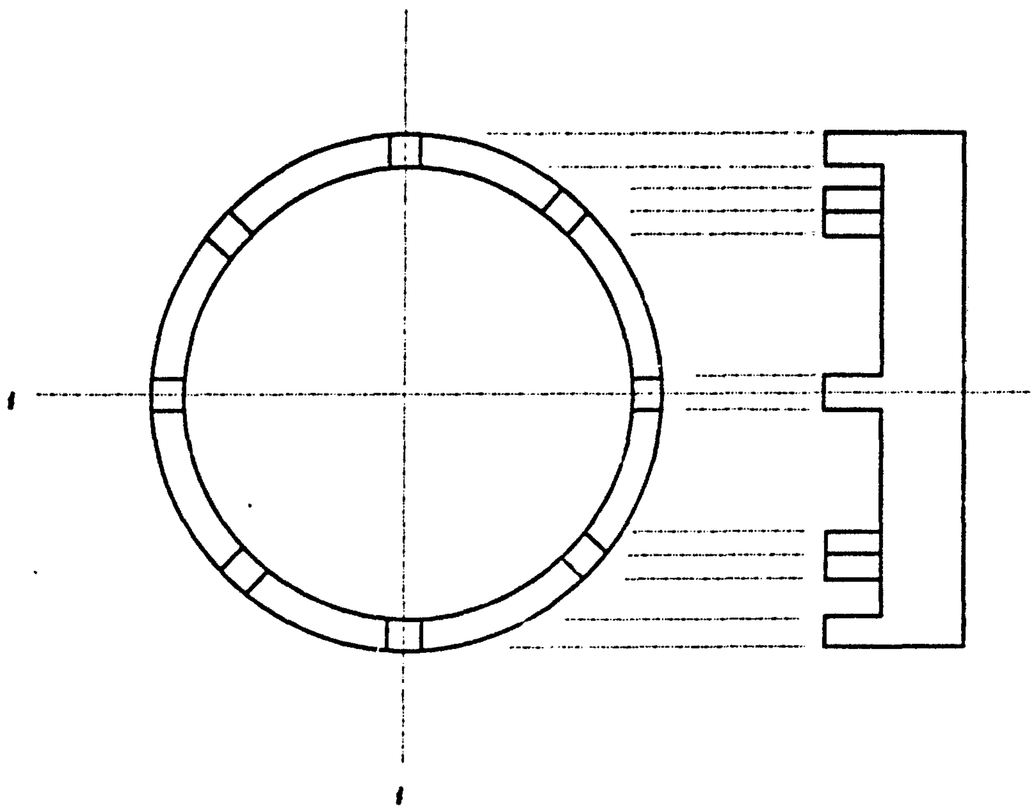

Figure 3. Adopted Configuration of Containment Shroud Standoff Ring

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varying concentrations, proper disposal in accord with federal, state, and local laws and regulations is required. Principal concern is with the solid wastes, since the filters will keep the discharge of lead paint particulates in water or air at concentrations below permitted levels.

Regulatory Requirements

Solid Waste. Under federal regulation 40 CFR 261.24,[17] solid wastes containing lead exhibit a hazardous waste characteristic.

All hazardous waste to be land disposed must first meet the requirements set forth in the Land Disposal Restrictions found in 40 CFR 268. Table CCWE[18] in §268.41 sets the treatment standard for lead as 5 mg/L as determined by stipulated test methods.[19] If the maximum concentration is exceeded, pretreatment is required before the lead-containing waste can be accepted for land disposal.

Pretreatment of hazardous materials can be accomplished by extraction, destruction, or immobilization. The following are procedures identified for pretreating lead waste:

- Immobilization in concrete isolates the contaminant from the environment. The waste must be presented in a homogeneous form; commercial waste disposal companies can provide homogenization by hammer mill treatment of the waste. Leaching tests of the final product is required before ultimate disposal.

- Incineration is feasible when the waste is seen as organic debris contaminated with metals, such as wood particles coated with lead-bearing paint. The Environmental Protection Agency (EPA) has set up a separate category for this and has offered the following guidance, 55 FR 22555, on dealing with the waste:

  "... as a matter of treatment policy ... prohibited wastes that are generated as an organo-metallic or in an organic matrix can be incinerated (in accordance with 40 CFR 264 or 40 CFR 265 Subpart O) to destroy the organo-metallic bond or the organic matrix containing the metal, prior to subsequent treatment of the ash. Incineration may be a preferred pretreatment, when the 'organic debris' are expected to contain organo-metallics or are otherwise impregnated with inorganic metal dyes or pigments (e.g., paints, paint chips, and/or resins)."

Note that the resulting ash must still be immobilized prior to land disposal.

Lead-bearing waste must meet the TCLP criteria and be placed in approved containers for storage according to 40 CFR 264 until disposal in a RCRA-approved landfill. Unless a RCRA Part B permit is in place, the allowed on-site storage time is 90 days from the date of generation.

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[17]Code of Federal Regulations, Protection of Environment, 40 CFR 261, *Identification and Listing of Hazardous Waste* (1992). Lead has been assigned the Hazardous Waste (HW) Number D008 by the Environmental Protection Agency (EPA).

[18]CCWE = Constituent Concentrations in Waste Extract.

[19]Treatment standards are based on EP Leachate analysis; this does not preclude use of TCLP (toxicity characteristic leaching procedure) analysis.

Air Quality. Ambient air quality is covered in 40 CFR 50 of the Code of Federal Regulations.[20] Two standards are applicable: total suspended particulates (TSP), and permissible lead concentration (PLC). For TSP, the primary standard[21] (§50.6) sets an annual geometric mean concentration of 75 $\mu g/m^3$ and a 24-hour limitation of 260 $\mu g/m^3$ (not to be exceeded more than once per year). The secondary standard (§50.7) of 60 $\mu g/m^3$ (annual geometric mean) is a guide for assessing implementation plans for achieving the 24-hour standard, while a maximum concentration of 150 $\mu g/m^3$ is not to be exceeded in a 24-hour period more than once in a calendar year.

For lead and lead compounds, measured as elemental lead (§50,12), both primary and secondary standards are a concentration of 1.5 $\mu g/m^3$ (maximum arithmetic mean over a calendar quarter).

Each state will have its own standards that may be more restrictive than those of the federal code. In Tennessee,[22] the federal guidelines were adopted in their entirety for both TSP and lead. The standard for lead was to be achieved and maintained thereafter by October 31, 1981; and for TSP, by December 31, 1982.

Water Quality. Lead is classified under EPA regulations as a priority pollutant; i.e., a hazardous material whose control by an indicated time is mandated. Because of its extreme biological hazard in human development, water quality regulations relative to lead and lead compounds emphasize the quality of water delivered to the user. Control focuses on eliminating introduction of lead into water bodies and on treatment to minimize lead in the public water supply. Implementation and control of requirements is relegated to the states. The primary source of lead in drinking water is from plumbing systems (lead-based solders, faucet components, lead pipes). However, improper removal and disposal of lead-based paints can add to the burden in water bodies that serve as drinking water sources and/or enter the food chain through plant absorption and fish/animal ingestion.

Waste Quantities

Paint. A typical military wood building (e.g., a barracks) could be of two-story height with overall exterior surface area, without allowance for windows, of about 10,000 ft^2. Window area might be about 1/3 of the total, giving a net area of 6,667 ft^2. Assuming multiple paint coats applied, the paint film thickness (as measured for a paint chip from a Fort Campbell, Kentucky, building) could be about 3/64 in. (1.2 mm). This yields a total volume of paint film of about 26 ft^3, if closely packed, or perhaps twice that volume ($\sim$50 ft^3) under more realistic packing as for randomly shaped flat particles. Allowing for diluents, air bubbles, etc. in the paint film, an average paint film density might be about 4-5 g/cm^3

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[20]Code of Federal Regulations, Protection of the Environment, Subchapter C—Air Programs, Part 50—National Primary and Secondary Ambient Air Quality Standards (1985).

[21]Primary is the level judged to provide an adequate margin of safety to protect the public health; and secondary is the level judged to protect the public welfare from any known or anticipated adverse effects of a pollutant.

[22]Rules of Tennessee Department of Public Health, Bureau of Environmental Services, Division of Air Pollution Control, Chapter 1200-3-3: Ambient Air Quality Standards (October 1, 1979).

(250-310 lb/ft^3).[23] Thus, the weight of the paint film to be disposed of could be as much as 8000 lb for a single building.

Wood. The density of yellow pine is 23-37 lb/ft^3 (0.37-0.60 g/cm^3). Assuming no more than 1/8-in. of wood removed, on the average, the total volume would be 69 ft^3 (compressed); and the total weight, between 1600 and 2550 lb. It is unlikely that significant amounts of lead compounds would have diffused more than 1/8-in. into the wood over the building lifetime.

Water. The quantity of water requiring disposal is limited, since the hydrojet process removes debris and then recirculates the water through the nozzle. Thus, on shutdown, the volume of water is the volume of the circulating system. The primary source of water loss in the flow circuit would be "squirting" from the containment shroud due to tipping. Water is not discharged from the system prior to removal of particulate and dissolved lead compounds.

The solubility of white lead in cold water is low (0.0017-0.0023 g/cm^3); thus, the amount of dissolved lead will be low. However, regulations require that the concentration of lead in the discharged water be as low as attainable with the best available technology (BAT). As noted above, the principal control seems to be at the use, rather than the discharge end.

The primary mode of removal for particulate fines would be by filters; coarser particles will have been removed in the centrifugal separator and the settling tank. The frequency (hence the volume) of filter disposal is difficult to estimate, deriving ultimately only from extended field experience. Some estimates could be obtained in a Phase II study of the water-debris separation system using simulated waste mixtures.

Treatment and Disposal

The hazardous waste resulting from this paint stripping process must be handled in accord with federal regulations and other more stringent state or community regulations as may locally apply. In general, such regulations require that the collection, transport, and disposal processes be done in such fashion as to prevent the hazardous material from entering either air or water bodies in concentrations above those proscribed. Only authorized disposal sites are acceptable. Temporary on-site storage in closed 55-gal drums before treatment and transport to permanent disposal is permitted.

All solid wastes discharged from the paint stripping system (except exhaust blower air filters) will be wet. They can be packaged in plastic bags and placed in drums for temporary storage and transport to the treatment and disposal sites. Because the wastes are non-volatile, they can be handled at the work location by an operator using a simple mouth/nose respirator and rubber gloves. Care should be exercised by the operator to avoid waste spills during packaging; a "floor pan" beneath the system could mitigate this problem.

If the wet waste must be moved over a long distance for treatment prior to disposal, transportation costs may be important; and dewatering of the waste may be required. Simply allowing the waste to drain over a period of time may be sufficient. Removal of water might be accelerated by using an air stream to "fluff" the waste mass; the air (possibly warm) would be introduced through a wand inserted to the bottom of the plastic bag containing the waste. Discharge of moist air from this process into the

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[23]White lead was the primary pigment used in earlier (pre-1980) paints. This was either basic sulfate ($PbSO_4.PbO$) with a density of 416.67 lb/ft^3 (specific gravity of 6.46) or basic carbonate ($2PbCO_3.Pb(OH)_2$) with a density of 432.15 lb/ft^3 (specific gravity of 6.70). Replacement white pigments, titanium or zinc white oxides, have specific gravities of 3.10 and 5.65, respectively.

work atmosphere should not pose a problem, though a filter could be added. For the filters, open dewatering may not be an option since fines could be carried into the ambient. A further, though more costly alternative, could be vacuum filtration.

"Spills" into the work area from tilting of the nozzle containment shroud or from mishandling of the waste can be accommodated by using a standard wet-dry vacuum. Such spillages should be minimal, once the operators acquire the simple skills of moving the shroud across the work surface and packaging the waste. The debris collected by the vacuum can be added to the other waste for disposal.

Overall, this proposed system is more efficient and cost-effective in handling and disposal of the lead-bearing waste than is current practice that encloses the building in a plastic "tent," covering the ground with plastic sheet, and isolating the operator with a respirator or atmospheric suit. In the latter context, contractors frequently wash the debris resulting from the stripping process into nearby storm sewers.

Disposal Costs

Disposal costs are variable, depending on the regulations applicable in the particular locale of the paint stripping operation and on the distance to an authorized disposal site. Labor costs may be sensitive to the production rate, requiring additional personnel at high stripping rates. Detailed cost estimates must await field experience.

Some insight can be gained from an Oak Ridge National Laboratory evaluation by Arnold et al[24] of a high pressure (35,000 psi) waterjet paint removal tool for stripping of vinyl and epoxy paints from ship hulls. They found that waste disposal was the primary cost factor, as well as the parameter with the greatest variability, ranging from $45/ton to $2000/ton depending on the waste classification and the location. From Wilkinson's[25] companion study, the average cost for paint removal was $2.82 per square foot when disposal cost was $50 per ton but rose to $3.27/ft² at $1000 per ton.

Cost Factors (Subtask 1.5)

Cost factors were derived from two sources: (1) data provided by commercial painting contractors, and (2) estimates based on a prototypic system.

Operator Experience

Estimates were obtained from several painting contractors for the cost of paint removal from several of the sources described in Subtask 1.1 above under the heading "Current Practice." Thus:

Brighter Concepts reported that their treatment cost prior to repainting is $0.05-0.10 per square foot for surface washing, depending on the nature of the surface and the condition of any coatings. However, for complete paint removal on badly deteriorated surfaces, their costs could be much higher, being dependent on paint condition, surface adherence, increased labor, cleanup requirements (dictated by EPA

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[24] J. G. Arnold, U. Gat, D. B. Lloyd, W. D. Venable, and V. K. Wilkinson, "Design of an Ultra High Pressure Waterjet Paint Removal Tool for Ship Hulls," Oak Ridge National Laboratory Report submitted to David Taylor Research and Development Center, draft.

[25] V. K. Wilkinson, "Life Cycle Cost Analysis of Shipyard Paint Removal Systems," Oak Ridge National Laboratory Report ORNL/TM-11613, Oak Ridge, Tennessee (May 1990).

permits), etc. Using their direct labor plus overhead cost figure of $300 per person-day and a production rate of 100-250 ft²/person-day, a treatment cost of between $1.30 and 3.10/ft² is obtained. Assuming a large two-story building (200×20×50 ft = 10,000 ft² of surface area), the total cost for stripping the outside walls of the building would be between $13,000 and $31,000. The latter figure corresponds to a period of performance of about 100 person-days.

Albert Bell says that his equipment and labor costs (two operators) run about $70/h. Assuming the same production rate as indicated above, this translates into a cost between $1.12 and $2.80 per square foot. This can be related to a reported cost of $0.10 to 0.50/ft² for sandblasting of concrete or metal.

As noted in Subtask 1.4, an ORNL study (Reference 25) provided a cost of $2.80/ft², assuming a 425,000 ft² annual demand, for coating removal on ship hulls *sans* waste disposal costs. This is consistent with the upper end of the cost estimate range given by the two painting contractors (above), although the ORNL system is much more sophisticated and operates at about ten times the pressure (35,000 psi). While ORNL says that over half of the cost is labor, their study suggests that scaleup economies are important. The report also states that the waterjet method "enjoys a substantial economic advantage over the commonly employed method of abrasive blasting with either garnet or black beauty grit."[25]

Prototype System

Costs were developed for a prototype system to be assembled for demonstration testing in a proposed Phase II study. The following assumptions guided this cost analysis:

(1) The system is to be portable, preferably wheeled-trailer mounted, to accommodate transport to and around the work site.

(2) The system is to operate without high voltage (220/440) primary electric power for the water pump or exhaust blower to increase site use flexibility.

(3) The system is to operate with a minimum of three separate nozzle/shroud units, each with capability equal to the laboratory-tested unit (5-7 gal/min at 1500 psi), to maximize performance of the waste removal system.

(4) The system should be capable of being operated by trained workers of average skill level.

(5) The system should have 95% or better water recycle to minimize need for on-site water supply and treatment.

(6) The system should have a minimum lifetime of 5000 hours of intermittent operation (8-10 h/day) for all major components.

(7) The system should be maintainable in the field.

(8) The system should have as low as attainable lead concentration in the water discharge to the drain and air discharge concentration of less than 7.5 $\mu g/m^3$ to the work ambient to satisfy federal regulations.

(9) The system should meet all OSHA standards for personnel exposure and safety.

The estimated cost of capital equipment items for this prototype demonstration system is given in ***Table 2***. The total capital cost, allowing 10% contingency, would be about $35,500. This latter number includes costs of field supplied items, such as supports, piping, fittings, hoses, filters, and electrical wiring.

For an estimated, practical lifetime of 5000 hours for the principal hydraulic components, based on suppliers' data, an amortized cost for capital items alone is about $7.00/hr. Allowing for operating costs for power (diesel fuel and electricity), maintenance of rotating equipment and other system elements, replacement nozzles, and non-specific labor, the amortized cost rises to about $11.50/hr. Based on a production rate of 100-250 ft^2/person-day as quoted by Brighter Concepts, and a labor rate of $30/hr (one skilled laborer and 2 helpers), the cost per square foot of board stripped could be in the range of $1.30 to $3.30.

This does not include waste disposal costs. From the previous section, waste disposal costs can be highly variable, being dependent on location. Using the cost range cited of $50-1000/ton and a solid waste generation rate 4 tons per $10,000 ft^2 building, an incremental cost of between 2 and 40 cents/ft^2 is developed.

From this rough estimate, the overall cost for paint stripping of the assumed building would range between $35,000 and $39,000, allowing a 6% profit margin, and would take about 3 months.

Equipment Sources (Subtask 1.6)

The prototype system shown in ***Figure 1*** includes the following principal components:

- High-Pressure Water Pump
- Pump Power Supply
- Exhaust Blower
- Cyclone Separator
- Settling Tank
- Containment Shroud
- Nozzles and Carrier (Wand)

For the purposes of a Phase II effort, it is proposed that these components be individually purchased and assembled into an operating unit by PAI Corporation. This provides the flexibility in design and modification needed for an effective field demonstration effort. The development of a "turn-key" package would be held off until Phase III.

The costs shown in the previous section were obtained through a survey of suppliers as listed in the Thomas Register.[26] This survey was not exhaustive; it was intended only that it be a point of departure for developing data supporting a more detailed design and a preliminary cost estimate. Some supplies and equipment (e.g., filters, standard supply and/or surge tanks, miscellaneous fittings and hoses) were not covered in this initial review; since it is not possible at this stage in development to estimate the requirements. ***Table 3*** identifies typical sources for component procurement.

[26]Thomas Register: Products and Services, Thomas Publishing Company, 1 Penn Plaza, New York (1992).

Table 2. Summary of Major Capital Equipment Required for Paint Stripping by Confined Hydraulic Jet: Prototype System

Component	Function	Description	Manufacturer (see *Equipment Sources*)	Approx. Cost
Water Pump	High pressure water to nozzle head	21.5 gpm flow at 3000 psig 21.8 gpm at 3000 psig	NLB Corp. Myers Corp.	\$6500 \$8500
Diesel Engine	Drive for high-pressure pump	49 hp, air-cooled 51 hp, water-cooled	Hatz Yanmar	\$6100 \$3830
Gear Reducer	Diesel to pump rpm	2.6:1	Harben	\$2000
Air Exhauster	Suction flow for head and separator	5 hp, 7000 rpm; -4 in. hg; 250 scfm	Lamson	\$3000
Cyclone-Type Separator	Primary solids removal	24x72 in. w/8-in. dump valve	Lamson	\$2800
Trailer Bed	System support/ transport	2½-ton capacity, 6 ft 4 in.x16 ft tandem axle	Trailer-Source	\$2000
Low-Pressure Tank	Make-up water supply	300 gal polyethylene	Plastic Piping Systems	\$850
Fixed Flow Nozzles	Water jet generation	0–15° spray angle	Graco Corp.	\$2000 (\$75/set)
Rotating Flow Nozzles	Water jet generation	Dual-tip spin blaster Turbo blaster	NLB Corp. Simpson Corp.	\$250 (incl. tips) \$250

Table 3. Confined Hydraulic Jet Paint Stripping System Equipment Sources

Water Pump	Harben Corporation	P. O. Box 2250 Cumming, GA 30330	(404) 889-9535 (800) 327-JETS
	Myers Pump Corp.		
	Pumps of TN (sales rep Myers)	306 N. Broadway Knoxville, TN	(615) 637-4172
	NLB Corp.	29830 Beck Rd. Wixom, MI 48096	(313) 624-5556
Diesel Engine	Power Unlimited • Hatz Corp (Germany) • Yanmar Corp (Japan)	401 Galway St. Knoxville, TN	(615) 525-1193
Air Exhauster	Lamson Corporation	Syracuse, NY 13221	
	LeCorp (sales rep Lamson)	P. O. Box 7508 Paducah, KY 42002	(502) 555-9653
Separator (Cyclone)	Lamson Corp.	See Air Exhauster	
Trailer Bed	Trailersource Corp.	117 Barber Rd, SE Marietta, GA 30060	(800) 241-4275
Water Tank	Plastic Piping Systems	2716 John Deere Dr. Knoxville, TN	(615) 525-1193
Nozzles	Graco Corporation	4050 Olson Highway Minneapolis, MN 55440	
	Graco S.E. Regional Sales Center	3560 Engineering Dr. Norcross, GA 30092	(404) 448-0733
	NLB Corp.	See Water Pump	
	Simpson Cleaning Systems	P. O. Box 4369 Clearwater, FL 34618	
	Lancaster Corp. (sales representative for Simpson cleaning)	P. O. Box 325 Pauline, SC 29378	(803) 583-3011

3 SCOPING STUDIES (TASK 2)

Objectives

The objectives of Task 2 were as follows:

(1) Identify feasibility issues based on the results of the Task 1 Definition Studies; and develop test plans for studying these issues (Subtask 2.1).

(2) Procure/fabricate prototypical equipment components; and assemble apparatus for laboratory scale studies (Subtask 2.2).

(3) Prepare/procure test samples; and characterize with respect to pertinent parameters (Subtask 2.3).

(4) Carry out limited testing sufficient to describe the protocol, problems, and potential of the hydrojet paint removal technique (Subtask 2.4).

(5) Obtain qualitative data on the behavior of a preliminary containment and collection shield (Subtask 2.5).

(6) Develop study plans for a possible Phase II program (Subtask 2.6).

Feasibility Issues and Test Plans (Subtask 2.1)

Feasibility Issues

The feasibility concerns to be addressed are fourfold:

(1) Can a water jet be used to strip paint from a wood surface such that all of the hazardous material (lead) is removed?

(2) Can a shroud surrounding the hydrojet prevent debris generated by the stripping action from being released into the work ambient?

(3) Can the water and debris be easily transferred from the operating head (shroud) to a separator/storage tank for subsequent treatment?

(4) Can a confined hydrojet paint stripping system be assembled that is simple in construction, convenient in operation, and low in cost?

An auxiliary issue, but one that is outside the scope of this present SBIR Phase I study, is:

(5) Can a paint-stripping process for wood be developed that leaves the surface in condition for repainting without significant refinishing but retains all of the advantages of the confined hydraulic jet system?

Test Plans

This study was performed in the laboratory in a separate effects context. The effect of each variable was examined independently of the other variables; the sum of the results will guide the subsequent (Phase II) development of an integrated paint removal (stripping) system. The test protocol was as follows:

- Identified, procured, and assembled all hydraulic components (pumps, nozzles, tanks, etc.). To the extent feasible, these were standard, off-the-shelf items so as to sustain the intent to develop a cost-effective system.

- Procured and prepared test specimens (cut, paint, dry, age). Panels cut from the boards were shuffled to randomize the blanks in respect to wood characteristics. Multiple panels were prepared for each wood type and each painting category (base, top, flat or gloss coats). Panels were selected arbitrarily from the pool for any given test.

- Performed tests over the span of the variables. Tests were carried out in arbitrary order with respect to the variables being studied. Exposed panels were photographed as the primary data record.

Equipment/Facility Descriptions (Subtask 2.2)

The test facility used for determining the effectiveness of a shrouded waterjet for removing lead paint from wood surfaces and containing the debris was assembled from standard off-the-shelf components. The principal elements, the high-pressure water supply and the test stand, are pictured in ***Figures 4 and 5***, respectively.

Water Supply

The high-pressure water spray system (***Figure 4***) was built around a three-plunger, positive displacement pump (TEEL Industrial Series Model 3P965) manufactured by the Dayton Electric Manufacturing Company, Chicago, Illinois, with an operating pressure up to 3000 psi. The compressor was driven by a 15-hp Lincoln electric motor (1750 rpm, 3-phase, 220/440 V) and had an output characteristic as shown in ***Figure 6***. Peripherals included an inlet line strainer, a regulating valve rated at 8-gal/min maximum flow over the 300-3500 psi range, and a Hydac pulsation dampener.

Test Fixture

The test fixture was designed to hold the spray nozzle at a fixed distance from the surface of the test specimen, while moving it at a steady (but variable) velocity across the face of the specimen. The fixture, shown in the photograph of ***Figure 5***, was fabricated of 2-in. aluminum angle and had an overall dimension of roughly 18-in. on a side. The specimen is mounted on the back face of the frame, and the spray wand with nozzle is clamped into a carrier (wood block) that moves horizontally in a carrier channel along the front face of the frame.

The carrier is driven in its channel by a gear motor (Dayton Right-Angle AC/DC) that rotates a threaded shaft (drive rod) extending through the carrier block. The drive rod turns within a nut fixed on one end of the carrier, thus carrying the block along the channel. This is shown schematically in ***Figure 7*** and in the alternately pictured view of ***Figure 8***. A rheostat control varies the motor speed and, hence, the carrier velocity; a reversing switch controls the direction of travel.

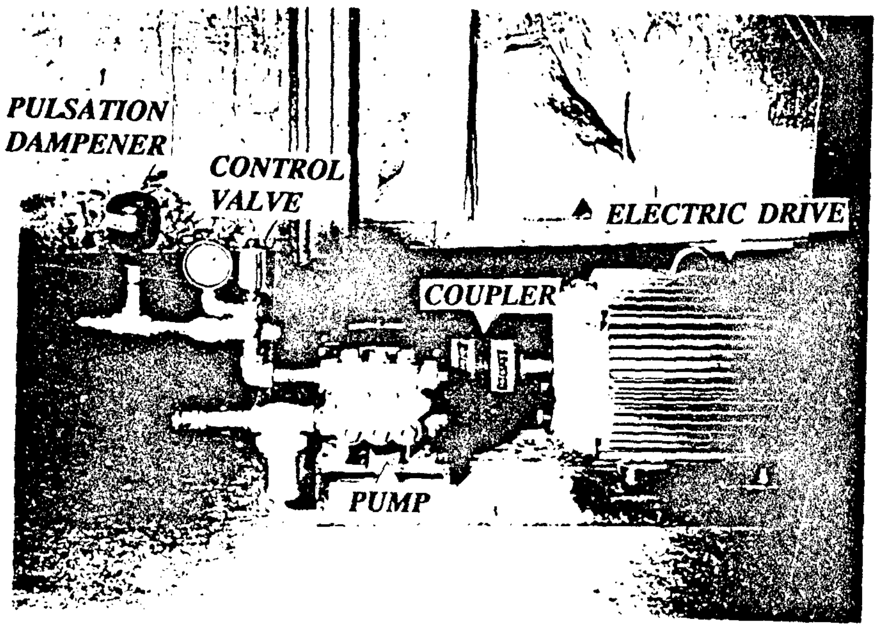

Figure 4. High-Pressure Pump for Water Delivery to Hydraulic Wand and Nozzle.

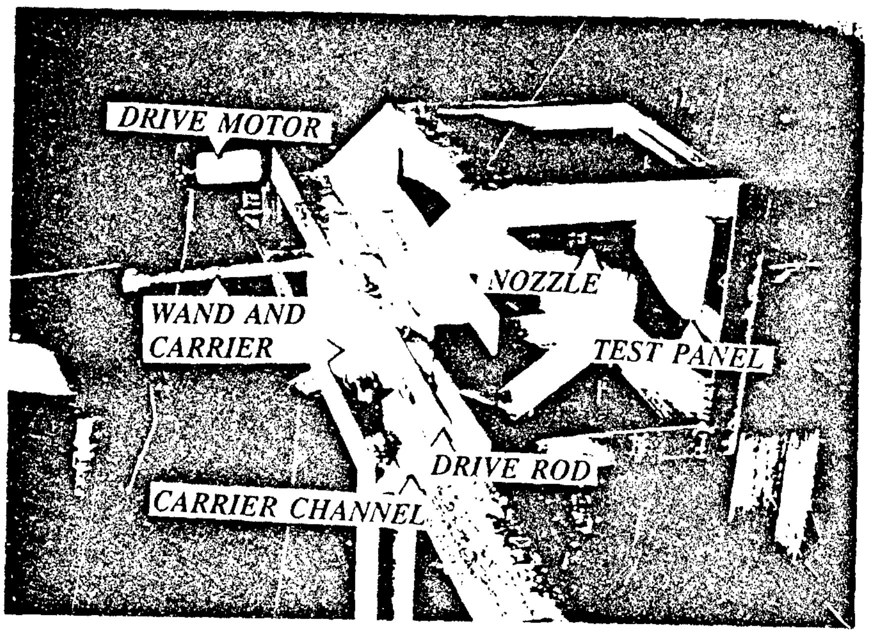

Figure 5. Test Stand Used in Study of Paint Removal by Hydraulic Jet.

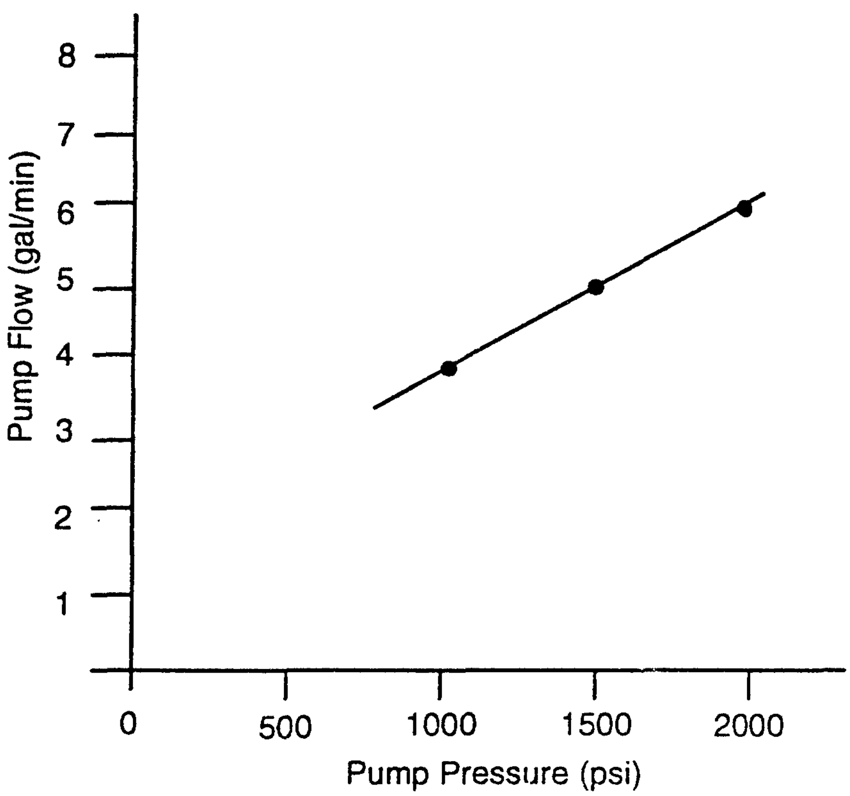

Figure 6. Operating Characteristic for TEEL Water Pump.

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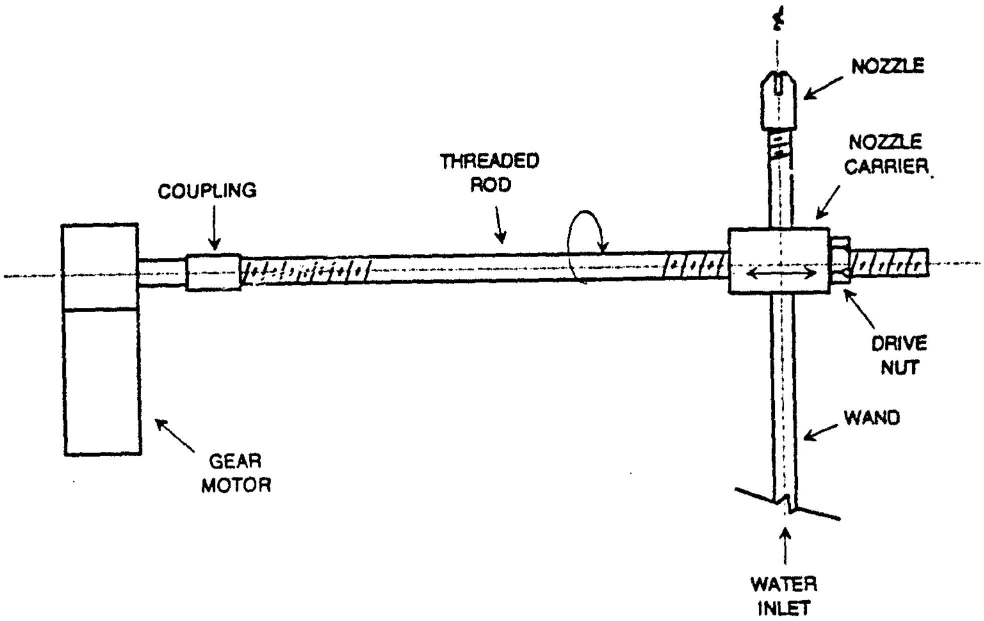

Figure 7. Schematic of Mechanism for Nozzle Drive.

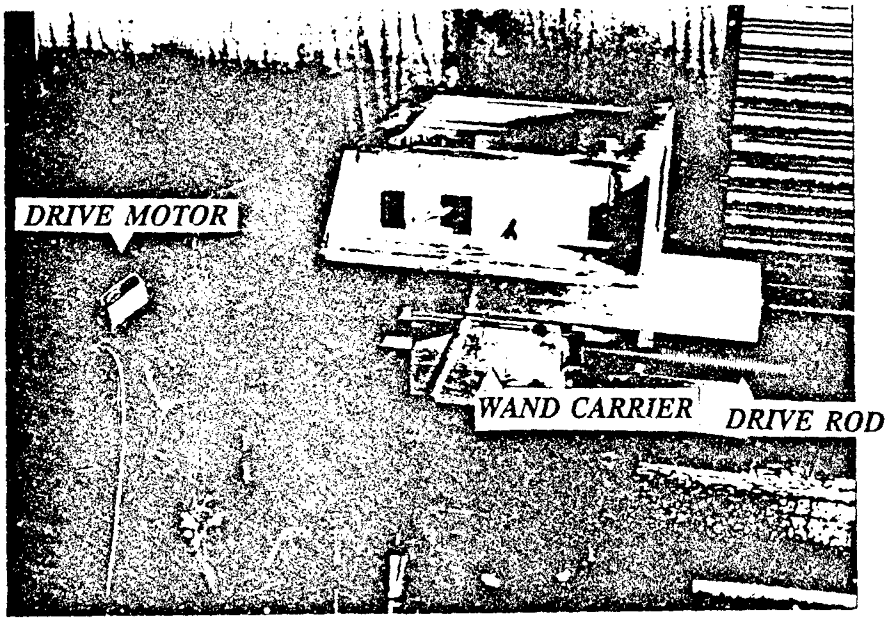

Figure 8. Test Fixture Showing Wand Carrier and Drive.

Containment Shroud

The containment shroud used in these scoping (feasibility) tests was formed from a PVC pipe tee with a 4-in. diameter run and a 2-in. diameter side port; this shroud is shown schematically in ***Figure 2*** and pictured in ***Figure 9***. A plug was inserted in one end of the tee, and the spray wand was inserted through the plug using a Swagelok fitting to accommodate wand movement along the axis of the tee. The open (nozzle) end of the tee was fitted with a notched PVC ring that was in turn wrapped with a soft (flexible) elastomer (rubber sheeting) band. This latter configuration is shown schematically in ***Figure 3*** and more clearly in the photograph of ***Figure 10***.

The side arm of the shroud was connected through flexible tubing to the inlet of a separator tank. The suction port of a Fuji regenerative compressor (Model VFC 503A-7W) (***Figure 11***) was connected to the outlet of the separator. The Fuji compressor has an unrestricted flow capacity of 150 ft^3/min and a shutoff head of 80-in. water.

The separator used in these studies was assembled from two available 55-gal stainless steel drums without heads at one end and with central PVC pipe fittings on the other face. The two drums were then joined at the open ends; this is shown in ***Figure 12***. In this Phase I study, the water and solid debris from the tests were merely collected in the separator tank and examined subsequently. No attempt was made to recirculate the water.

Spray Wand and Nozzles

A heavy-duty spray wand was obtained commercially for use in this study. The wand, rated at 3000 psi and 8 gal/min, is shown being used manually in ***Figure 13*** during early scoping tests.

The fan spray nozzles (***Figure 14***) used in these tests were manufactured by Spraying Systems Company; the characteristics of these nozzles are as follows:

Catalog Number	Identification Number	Jet Angle (deg)	Orifice Size (in.)	Flow Rate (gpm)[1]
2P604	4.	15	0.052	3.1
2P603	5.5	15	0.060	4.4
2P602	8.	15	0.072	6.2
˜P065	Set	0,25,40,65	0.072	4.0[2]

[1] At 2500 psi
[2] At 1000 psi

A rotating head accommodating two nozzles was obtained from NLB Corporation (see ***Figure 14***). The nozzles are located equidistantly at 0.6 in. from the axis of rotation.

Figure 9. Debris Containment Shroud.

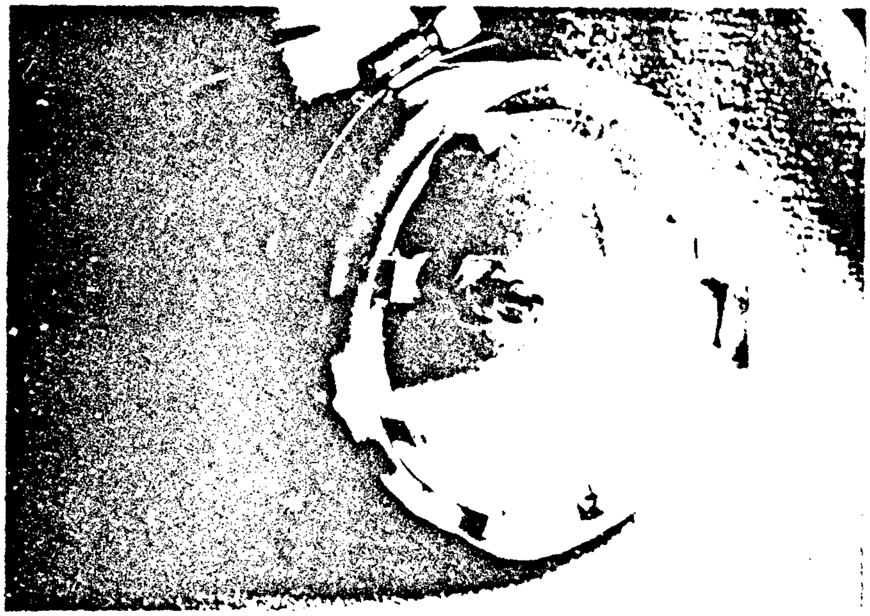

Figure 10. End View of Containment Shroud.

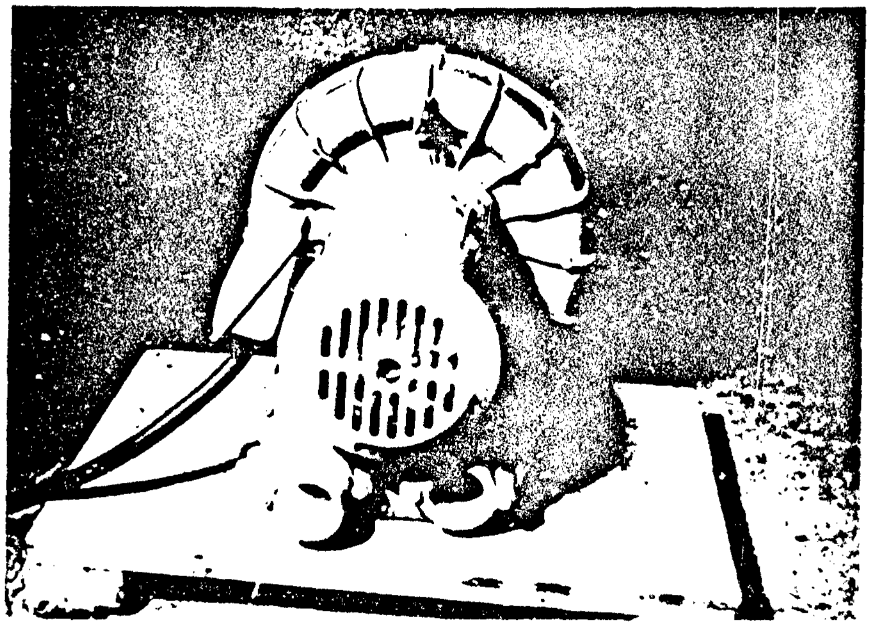

Figure 11. Air Exhauster for Debris/Water Extraction from Containment Shroud.

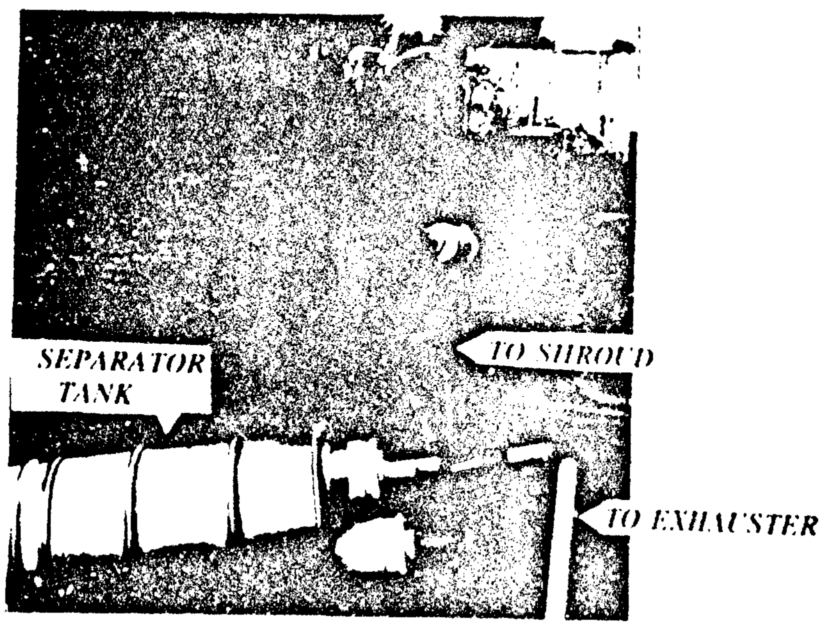

Figure 12. Debris/Water Separator Showing Connections to Shroud and Exhauster.

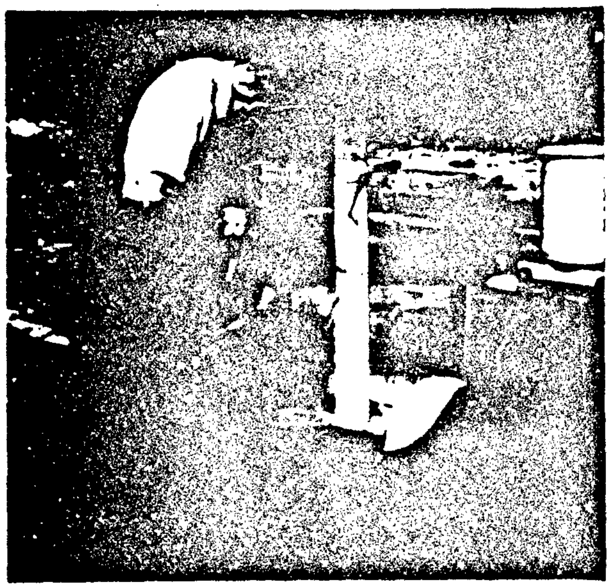

Figure 13. High-Pressure Wand in Manual Use for Scoping Studies.

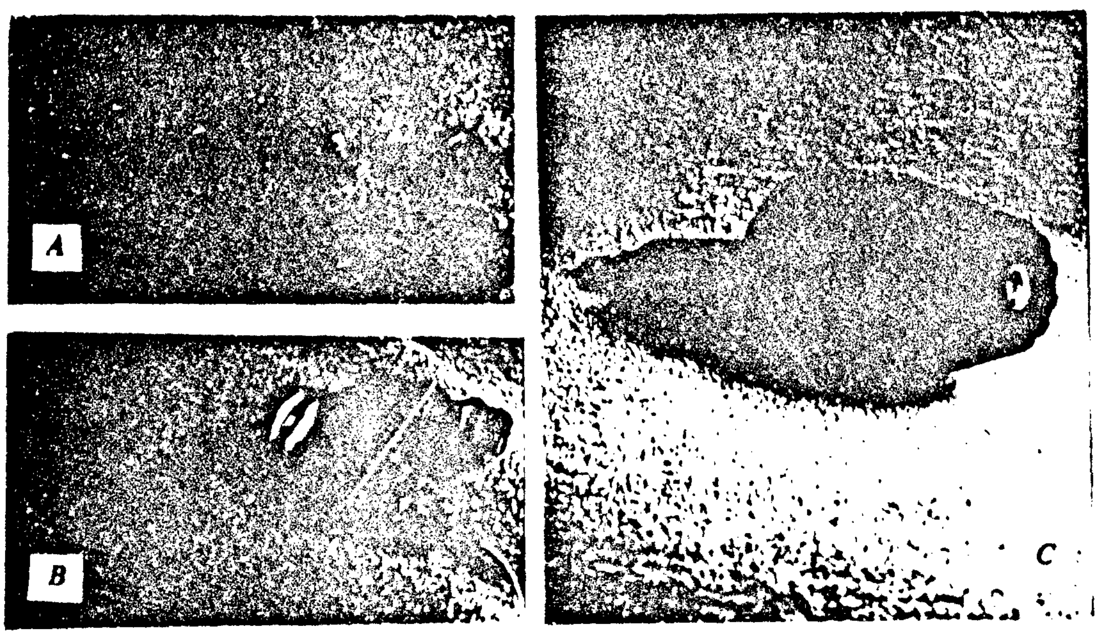

Figure 14. Nozzles Used in Experimental Studies.
(A) Fixed Spray; (B) Rotating Head; (C) Rotating Jet

Test Procedures (Subtask 2.3)

Specimen Preparation

Standard specimens were fabricated from several different woods:

- pine siding (1-in. by 6-in. boards),
- fir plywood (a 4-ft by 8-ft, 5-ply sheet), and
- oak shelving (1-in. by 6-in. boards).

Specimens were cut to 5.5-in. square dimension; and edges, but not surfaces, were sanded.

Specimens for initial tests were prepared by painting the front surfaces with a primer (sealer) and then one or two coats of exterior latex flat, exterior latex gloss, or exterior oil-base gloss paints. Painted surfaces were allowed to air-dry in the laboratory ambient at least twenty-four hours between coats. All paints were off-the-shelf, without color pigment (i.e., white), and lead-free. Until used, the individual specimens were stored flat (not stacked) with the painted surface facing upward (***Figure 15***).

A subset of the specimens (several of each type of wood with each type of paint) received accelerated light and heat aging under an array of heat lamps. The sample rack loaded with test specimens is pictured in ***Figure 16***; the light array, consisting of six 250-watt lamps, is shown in ***Figure 17***. Panel exposure was from a distance of 18 to 24 in., and exposure time has varied from several weeks to several months. Significant surface warming was experienced with the paint reaching and being maintained at temperatures in the 75-85°F range. No specimens received natural weathering, since the time involved would have extended beyond the period of this Phase I study.

A second test subset was prepared by giving a number of panels multiple coats of paint (up to 10) with 48 or more hours of air drying between coats.

An attempt was made to acquire painted exterior siding boards from an old (WW II vintage) building scheduled for demolition. This was unsuccessful,[27] but a sample of paint film that had peeled from one such building at Fort Campbell, Kentucky, was obtained. These "chips", collected from the ground adjacent to the building, were roughly of 2.5-3.0 in. by 3.5-5.0 in. in area and 0.055-in. thickness. A typical cross section is sketched in ***Figure 18***. The chips had considerable strength (i.e., could support their own weight when held horizontally by one edge) but were brittle (i.e., fractured cleanly when subjected to a bending force). One such sample was prepared for testing with a water jet by lightly gluing the chip to a wood panel.

Test Procedures

In performing tests, a painted panel was mounted (with the grain horizontal) in a support frame that was in turn clamped onto the rear face of the test fixture (see ***Figure 5***). The nozzle, carried at the end of the wand supported in the carrier block, was moved across the specimen parallel to the grain at a rate determined by the control rheostat setting (e.g., 10 = 15 in./min). The separation of the nozzle from

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[27]The lead-based paint on the building siding is a hazardous material under federal regulations. Removal and transfer requires preparation of significant paperwork on the part of both the donor and the receiver, including development of ultimate disposal plans. Thus, obtaining a laboratory-sized sample did not seem feasible.

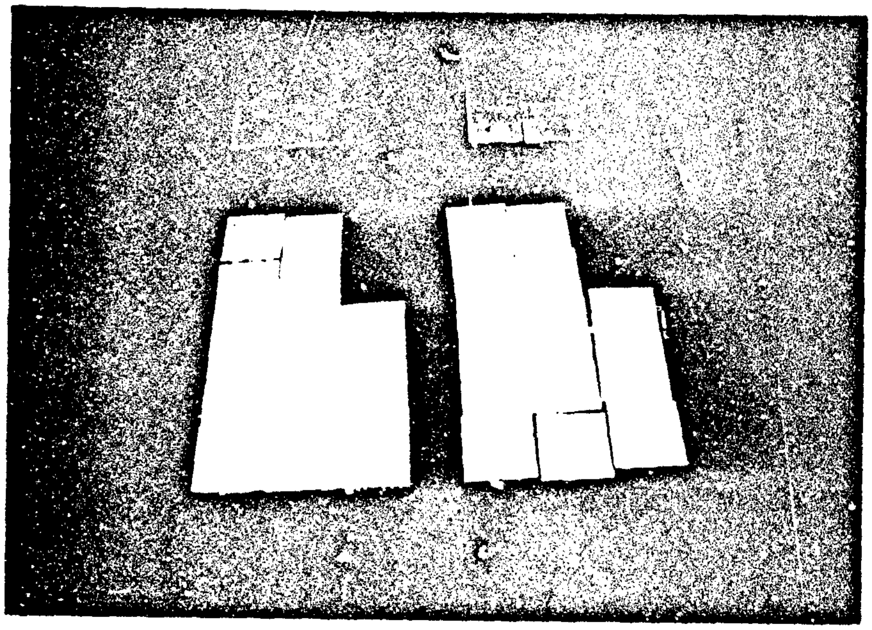


Figure 15. Wood Panels during Painting and Storing.

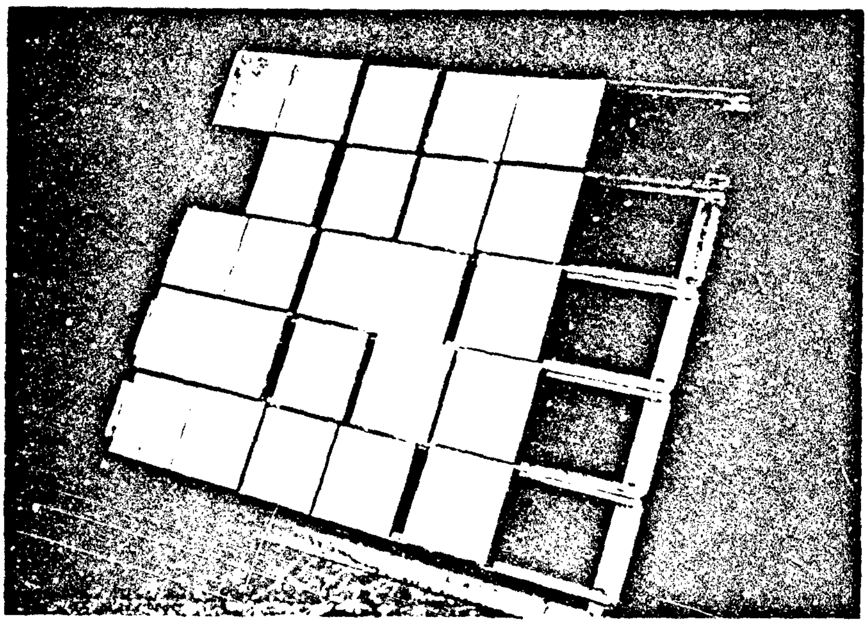


Figure 16. Test Specimens Mounted on Rack for Heat/Light Aging Exposure.

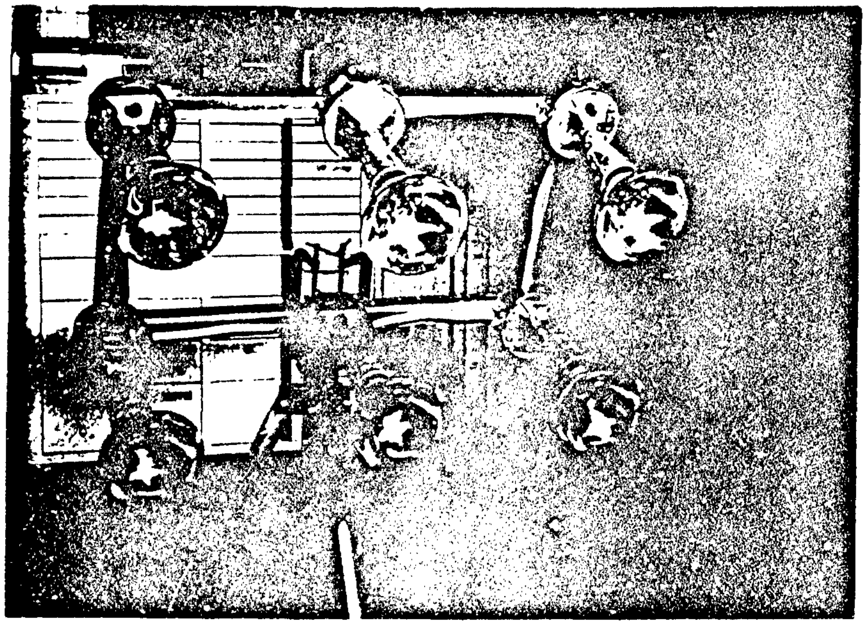


Figure 17. Heat Lamp Array for Aging of Test Panels.

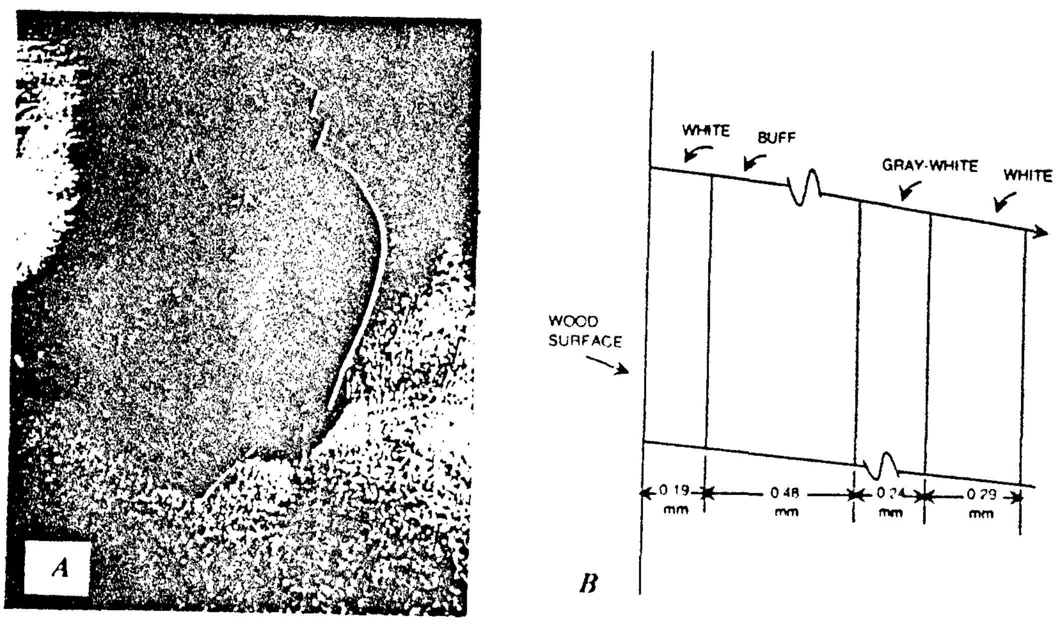


Figure 18. Fort Campbell Paint Chip Sample.
(A) Photo view (~3 x 5-in.)
(B) Cross section; dimensions appx.

the specimen surface was set manually at 1, 2, or 3 in. Most tests were done with a 15-degree nozzle oriented such that the spray fan was vertical (across the grain). The nominal operating pressure was 1500 psi.

Tests involved setting the traverse rate, pump pressure, and separation parameters for a given nozzle and passing the water jet across the specimen. In most cases, the test constituted two passes; i.e., the jet traversed the specimen, was reversed, and retraced the initial path in returning to the starting position. Tests having multiple passes were usually done in two-pass steps. Effects were noted at the end of each pass.

Test Results (Subtask 2.4)

Several series of tests were performed to (1) checkout apparatus behavior, (2) define a testing protocol, (3) determine the effectiveness of a hydraulic jet in removing paint from a coated surface, and (4) demonstrate debris containment. Separate effects tests were the primary vehicle for studying feasibility; i.e., removal, extraction, and separation were examined separately.

Scoping Tests (Subtask 2.4.1)

Preliminary studies were carried out to examine the operating characteristics of the assembled hydraulic jet system (see Subtask 2.2) and to observe the general effectiveness of the jet in removing paint.

Hydrojet Tests. These tests used several available painted boards:

(1) Cedar siding coated initially with several applications of an oil-based stain and subsequently covered by a single coat of an outdoor latex paint; this board had been exposed to outside weathering over a period of about 20 years.

(2) A pine shelf board with two coats of an interior latex that had been applied about 30-years ago.

Both cedar and pine are soft woods.

The tests were done using a fan spray nozzle with a spray angle of 30-degree and operating pressures between 1200 to 1500 psi. The spray wand was handheld at a distance of about 2 in. from the surface; this was maintained by a wire extending from the nozzle end of the wand. The orientation was roughly vertical to the painted surface.

In the first attempt at paint removal, the jet attack was in the center of the painted area of the board. There was no visual evidence of paint removal at the particular jet strength (i.e., spray angle, pressure, displacement, and orientation) of the test. In subsequent trials with the water jet traversing inward toward the center from the unpainted edge of the board, removal of paint from the surface initiated more easily as the jet dug into the soft wood along the board edge. The primary mechanism for paint removal seemed to be by wood splintering rather than by cracking or other attrition of the paint film. The principal attack was along the softer grain portions of the surface, giving the surface the appearance of exposed termite tunnels. Paint remained on the still-raised, harder grain portions.

In a second test set, a 15-degree jet angle spray was used with the same boards. The nozzle had a nominal flow rating of 6.2 gal/min at 1500 psi and was held at approximately 3-in. from the painted surface. Paint removal from the cedar substrate started more easily with this nozzle, but wood was removed in larger splinters than observed previously. Again, paint-covered "mesas" were left; this is

visible in the photograph of *Figure 19*. These could be removed by a second or third water-jet pass. The resulting exposed bare wood was very rough, being deeply splintered, and not in condition for repainting without substantial repair. Typical of the splinters formed are those shown in *Figure 20*. While the ability to repaint the surface after removal of the original paint is desirable, it is not a stipulation of this Phase I feasibility study.

A third preliminary test looked at paint removal on the pine board substrate. In general, behavior was as observed with the cedar board, that is splintering and deep gouging. However, in one area where the top coat was of a different color than the underlying paint film, it was noted that only the top coat was removed during a short exposure period. When observed under an optical microscope, this region showed flaking off of the outer coat while the inner coat remained adherent.

Surface Abrasion. Mechanical abrasion of the paint surface prior to exposure to the water jet was examined in these scoping studies as a possible pretreatment to improve performance of the hydraulic jet in paint removal. Based on the observations described above, it was presumed that "breaking" the paint film might improve the effectiveness of the jet in lifting the paint from the surface. A scoring device, such as a wire brush or a rake of pointed tines, when mounted within the containment shield housing the jet nozzle might serve this purpose.

The results of a limited test using a rotating wire brush on the painted cedar are pictured in *Figure 21*. As noted in the upper right region of the photograph, mechanical abrasion can remove the paint down to the bare wood surface. If mounted within a containment shroud, the generated waste could be contained and extracted from the work surface for subsequent disposal. However, the process is long and tedious and would not satisfy the premises of this study for a cheap and rapid means for paint removal attendant to structure demolition.

On the upper and middle left in the photograph, wire brushing was stopped before completing removal of the paint film. This left a thinner and broken paint layer. The water jet was then used to remove the remaining paint; this is shown in the lower right and left. In both the partially stripped (left) and the bare (right) areas, exposed wood was removed without significant further attack on the painted portions.

Substrate Effect. The effectiveness of the water jet in removing paint from surfaces harder than wood was examined qualitatively. The test objects were an outside concrete pad and an exposed angle-iron frame. On the concrete surface (*Figure 22*), paint spots and accumulated dirt and rust stains were removed without difficulty. Removal of paint and rust from the iron frame, which is a smoother and less porous substrate, was not as easily accomplished, requiring multiple passes at the jet strength of these scoping tests. The latter result is shown by the darker gray areas in *Figure 23* on the vertical leg immediately below the horizontal weld.

Feasibility Tests (Subtask 2.4.2)

Runs were conducted to determine the effect of the several relevant variables on paint removal from the wood test panels described in Subtask 2.3. The tests have been organized into series that examine the following parameters:

Grain orientation	Nozzle-surface separation
Type of substrate	Nozzle pressure level
Paint coat thickness	Nozzle spray angle
Nozzle-surface angle	Surface pretreatment
Number of passes	Nozzle traverse velocity

Figure 19. Cedar Board after Hydrojet Exposure. Paint-covered mesas remain after traverse.

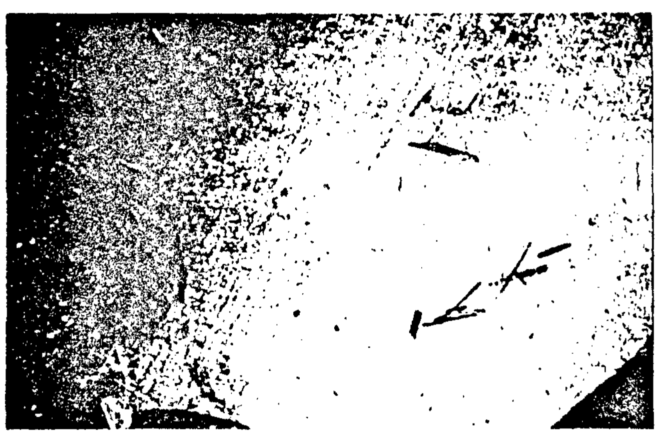


Figure 20. Typical Splinters from Cedar Board.

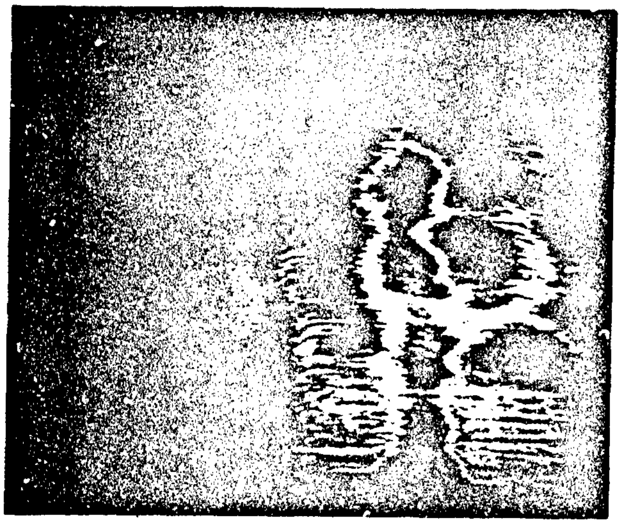


Figure 21. Scoping Test with Wood Surface Abraded Prior to Hydrojet Exposure.

Figure 22. Scoping Test with Hydrojet on Concrete Surface.

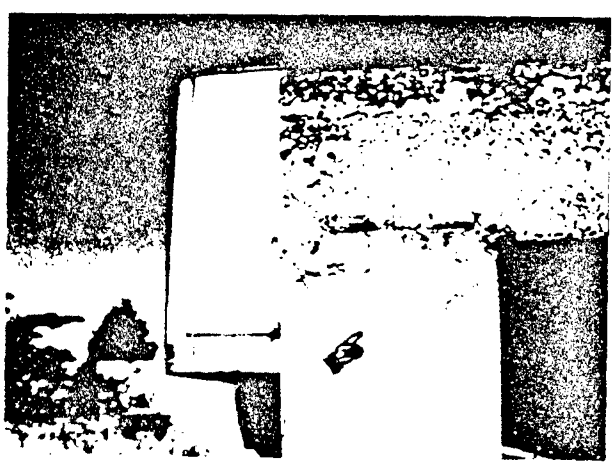


Figure 23. Rust and Paint Removal by Hydrojet on Steel Substrate.

Test series are identified in ***Table 4***; and the conditions for each run, in ***Table 5***. A test run generally consisted of two passes across the surface; namely, a traverse from right to left, followed by reversal and a traverse from left to right. Except for Test Series 700, the nozzle was oriented perpendicularly to the test surface. The carriage speed was 15 in./min in most runs.

While the tests were performed under controlled test conditions, the data recorded were qualitative only, being derived from visual examination and photographic record after exposure of the specimen to the water jet. Emphasis was placed on tests with pine siding specimens as most typical of building construction. Note that individual tests may "fit into" several different test series. Results were in summary:

Test Series 100: Effect of Grain Orientation

TS-101. Two initial tests (designated as Runs R-1 and R-2) were performed to examine the effect on paint removal of nozzle travel with or across the wood grain. The tests were done with specimen 48P and 49P, respectively, pine substrates with one primer coat. Nozzle pressure level was held to 1000 psi, so as not to obscure the results by excessive paint and wood removal. Full test conditions were as listed in ***Table 5***; results are shown in ***Figure 24***. It was observed that:

(1) Across the grain traverse removed paint and wood in the soft grain zones but left paint on the hard ridges.

(2) Along the grain traverse cut deeply into the soft wood between the growth rings.

All subsequent tests were done with nozzle traverse along the grain, in order to emphasize the impact of the variable being examined on paint and substrate removal.

TS-102. This test is extracted from a test series performed sequentially later in the experimental program. It is included here as relevant to the discussion of the effect of grain orientation on paint removal by hydrojet. Run R-5 was carried out at a nozzle pressure of 1100 psi using the pine test panel 44P (single primer coat). The results for nozzle-surface separations of 1, 2, and 3-in. are shown later in ***Figure 26***. A cross sectional view of the test panel is sketched in ***Figure 25***; observations are given relative to this figure.

(1) At the 1-in. nozzle-surface separation, attack is into the soft wood portion of the growth ring. The depth of paint/wood removal is 0.125 to 0.1875 in. along the full length of the nozzle traverse.

(2) At the 3-in. nozzle-surface separation, removal is again in an area having broad soft wood regions running parallel to the nozzle traverse direction; the depth of the "cut" is 0.0625 to 0.125 in.

(3) At the intermediate separation of 2-in., the nozzle traverse seems to be across a region of core wood with hard zones in close juxtaposition; this orientation is similar to the cross grain condition examined in TS-101. Paint removal is limited; and wood gouging, negligible.

Test Series 200: Effect of Nozzle-Surface Separation

Two tests (Runs R-3 and R-4) were performed to examine the effect of nozzle distance from the test surface on paint removal. The tests used panel 50P, a pine substrate with a single primer coat. As in Series 100, the nozzle pressure was 1000 psi; full test conditions were listed in ***Table 5***.

Table 4. Index of separate-effects tests performed in feasibility studies on paint removal by confined hydrojet

Test Series	Variable	Runs
100	Grain Orientation	R-1, R-2, R-5
200	Nozzle-Surface Separation	R-3, R-4
300	Substrate Material	R-5 to R-13
400	Hydrojet Rotation	R-14, R-15, R-37 to R-39
500	Surface Aging	R-16 to R-21, R-36
600	Nozzle Inclination	R-22, R-23, R-24
700	Pressure Level	R-25 to R-29
800	Jet Passes	R-30, R-31
900	Materials Observations	—
1000	Surface Pretreatment	R-34, R-35
1100	Multiple Coatings	R-40, R-41
1200	Nozzle Spray Angle	R-42
1300	Nozzle Flow Rate	R-40, R-41

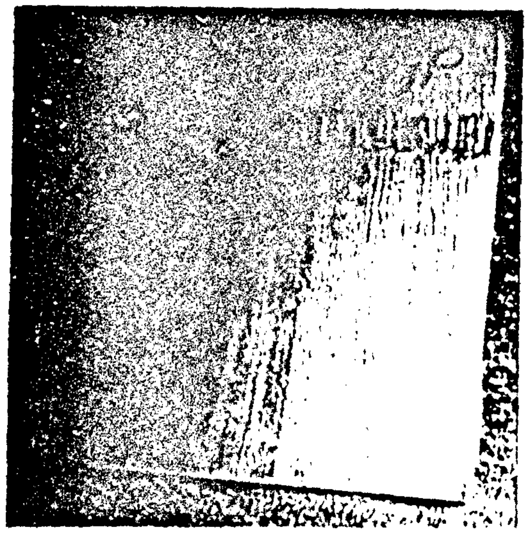
Table 5. Test conditions for studies on hydrojet paint removal from wood substrates

Run Number	Panel Number[1]	Nozzle Angle (deg)	Nozzle Tilt[2] (deg)	Nozzle Pressure (psi)	Nozzle Distance (in)	Traverse Passes	Traverse Speed (in/min)	Coating[3]
R-1	48P	15	0	1000	2	2	15	A
R-2	49P	15	0	1000	2	2	15	A
R-3	50P	15	0	1000	3	2	15	A
R-4	50P	15	0	1000	2	2	15	A
R-5	44P	15	0	1100	1,2,3	2	15	A
R-6	64PP	15	0	1000	1,2,3	2	15	A
R-7	35Q	15	0	1000	1,2,3	2	15	A
R-8	67P	15	0	1500	1,2,3	2	15	A
R-9	61PP	15	0	1500	1,2,3	2	15	A
R-10	31Q	15	0	1500	1,2,3	2	15	A
R-11	11P	15	0	1500	1,2,3	2	15	C
R-12	13PP	15	0	1500	1,2,3	2	15	C
R-13	8Q	15	0	1500	1,2,3	2	15	C
R-14	68P	15	0	1000	4	2	15	C
R-15	87P	15	0	1000-1400	2	2	15	C
R-16	14P	15	0	1500	1,2,3	2	15	C'
R-17	14PP	15	0	1500	1,2,3	2	15	C'
R-18	9Q	15	0	1500	1,2,3	2	15	C'
R-19	9P	15	0	1500	1,2,3	2	15	B'
R-20	9PP	15	0	1500	1,2,3	2	15	B'
R-21	6Q	15	0	1500	1,2,3	2	15	B'
R-22	13P	15	30	1500	1,2,3	2	15	C
R-23	11PP	15	30	1500	1,2,3	2	15	C
R-24	7Q	15	30	1500	1,2,3	2	15	C
R-25	23P	15	0	0	3	2	15	E
R-26	23P	15	0	500	3		15	E
R-27	23P	15	0	700	3		15	E
R-28	23P	15	0	900	3		15	E

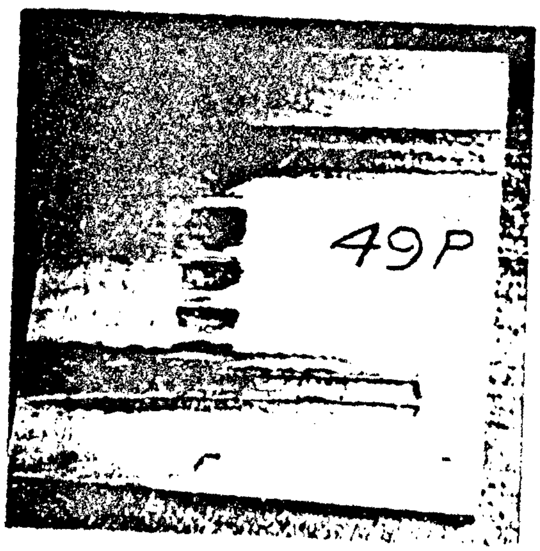
Table 5. Test conditions for studies on hydrojet paint removal from wood substrates (continued)

Run Number	Panel Number[1]	Nozzle Angle (deg)	Nozzle Tilt[2] (deg)	Nozzle Pressure (psi)	Nozzle Distance (in)	Traverse Passes	Traverse Speed (in/min)	Coating[3]
R-29	23P	15	0	1100	3		15	E
R-30	23P	15	0	700	3		15	E
R-31	23P	15	0	900	3		15	E
R-32	22P	15	0	700	3		15	E
R-33	22P	15	0	900	3		15	E
R-34	22P	15	0	700-1100	3		15	E
R-35	21P	15	0	700-1100	3	Multi	15	E
R-36	47P	0	0	650-1500	2	---	15	FC
R-37	84P	15	0	1500	3	2	15	A
R-38	105P	15	0	1500	3		15	A
R-39	104P	15	0	1500	3		15	A
R-40	30O̲	15	0	1500	2		15	F
R-41	30O̲	15	0	1500	2		15	F
R-42	85P	0	0				15	

[1] P = pine; PP = fir plywood; O̲ = oak.
[2] Tilt (inclination) from vertical; vertical = 0-degree.
[3] A = primer
B = primer + 1 coat exterior latex (flat)
B' = B + heat/light aged
C = primer + 2 coat exterior latex (flat)
C' = C + heat/light aged
D = primer + 1 coat exterior latex (gloss)
E = primer + 2 coat exterior latex (gloss)
F = primer + multicoats exterior latex (flat)
FC = Fort Campbell paint chip



(a) Run R-1
Across Grain



(b) Run R-2
With Grain

Figure 24. Grain Orientation Test Results (TS-100).

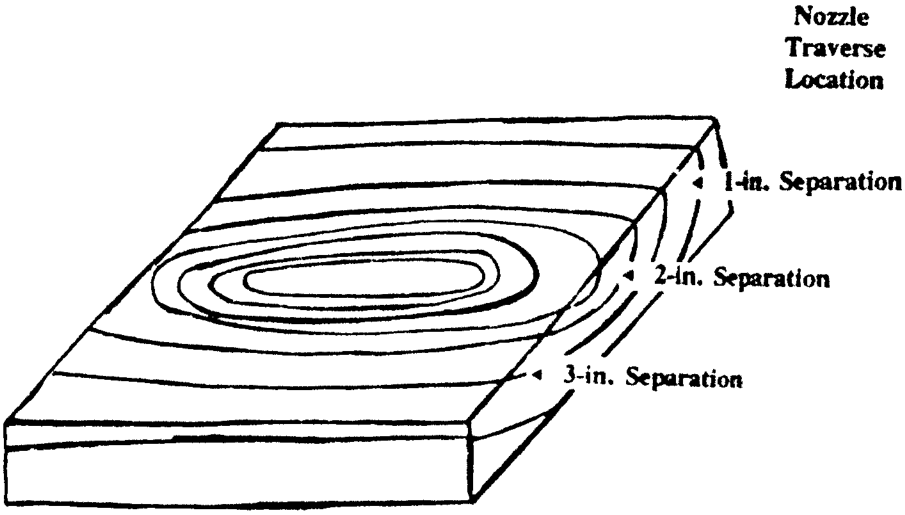
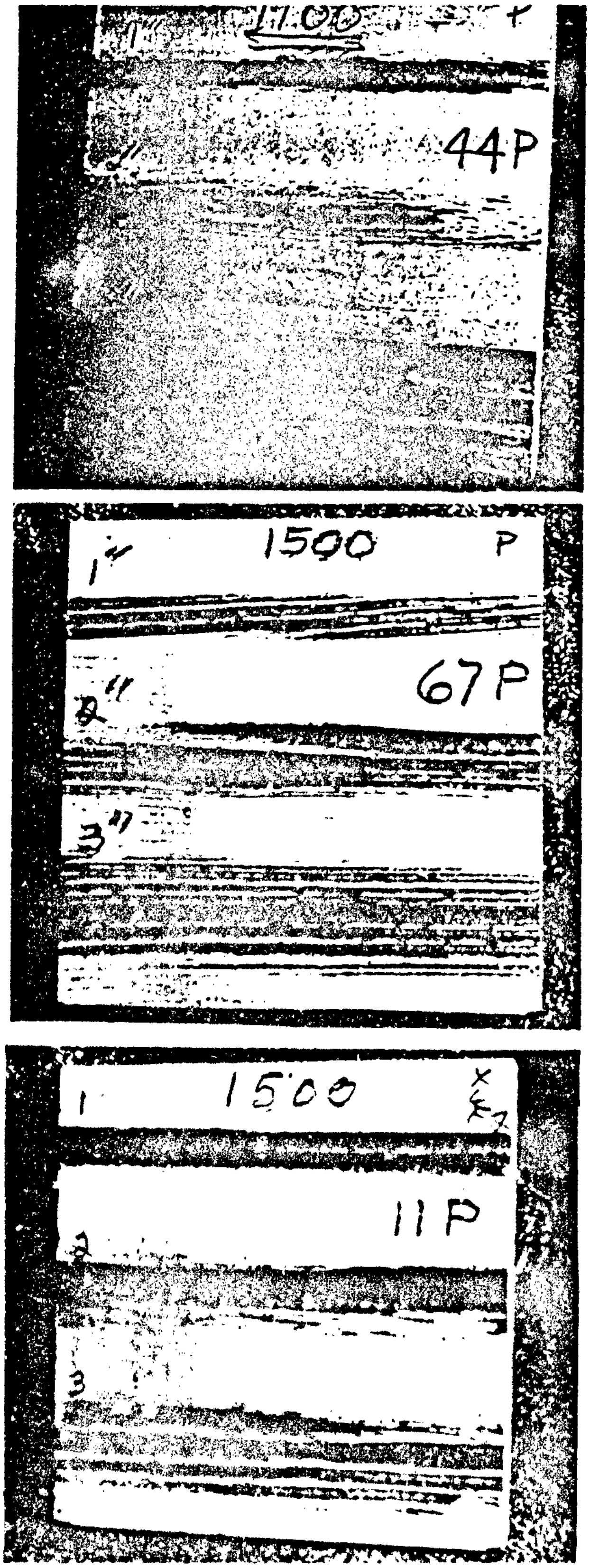


Figure 25. Sketch of Wood Grain Structure as Seen in Test Panel 44P.



(a) **Run R-5**
1100 psi
Primer

(b) **Run R-8**
1500 psi
Primer

(c) **Run R-11**
1500 psi
Primer + 2 Exterior

Figure 26. **Pine Substrate Test Results (TS-300).**

It was observed that there was a discernible increase in the dimension of substrate removal (both width and depth) as the nozzle was moved inward from a separation of 3-in. (R-3) to one of 2-in. (R-4). A subsequent test (R-8 with panel 67P), performed at a higher nozzle pressure of 1500 psi but otherwise identical test conditions, showed deeper gouging at 2-in. separation than had been observed at the 1000-psi level (see ***Figure 26.B***).

Test Series 300: Effect of Wood Substrate

This series comprises several sets of tests to examine the characteristics for paint removal on such different substrates as pine, fir plywood, and oak. Tests were carried out at several pressure levels, at several nozzle-surface separations, and with single or multiple paint coats. Traverses were made on each test panel at 1-in., 2-in., and 3-in. nozzle-surface separation. A listing of conditions for each of the tests is given in ***Table 5***.

TS-301. This test set consisted of Runs R-5 to R-7. Runs were carried out at a nozzle pressure of 1100 psi with panels 44P (pine), 64PP (fir plywood), and 35Q (oak), each having a single primer coat. Results, shown in the level-A photographs of ***Figures 26*** through ***28***, are summarized as follows:

(1) The width of the band of paint removal increased with nozzle-surface separation, being widest at 3-in. and least at 1-in.; this is consistent with the distance at which the surface intercepts the broadening fan spray.

(2) Paint removal (and substrate wood gouging) was most on the softer pine panel and least on the harder oak panel at all nozzle-surface separations.

TS-302. This second test set, comprising Runs R-8 to R-10 (panels 67P, 61PP, and 31Q, respectively), differed from TS-301 only in the nozzle pressure was increased to 1500 psi. It was observed from the level-B photographs in ***Figures 26*** through ***28*** that paint removal was more extensive than, but otherwise consistent with, the results from the previous tests.

TS-303. The final tests grouped in this series are Runs R-11 to R-13 carried out with panels 11P, 13PP, and 8Q, respectively. The nozzle pressure was again 1500 psi (as in TS-302), but the panels were coated with a primer coat plus two layers of exterior flat latex. Results are shown in the level-C photographs of ***Figures 26 to 28***. Interestingly, paint removal was qualitatively greater on all three substrates than observed in TS-302. Some wood fiber fuzzing was noted at the 1- and 2-in. separations with both the pine and fir samples. Overall, the results were similar to those of TS-302.

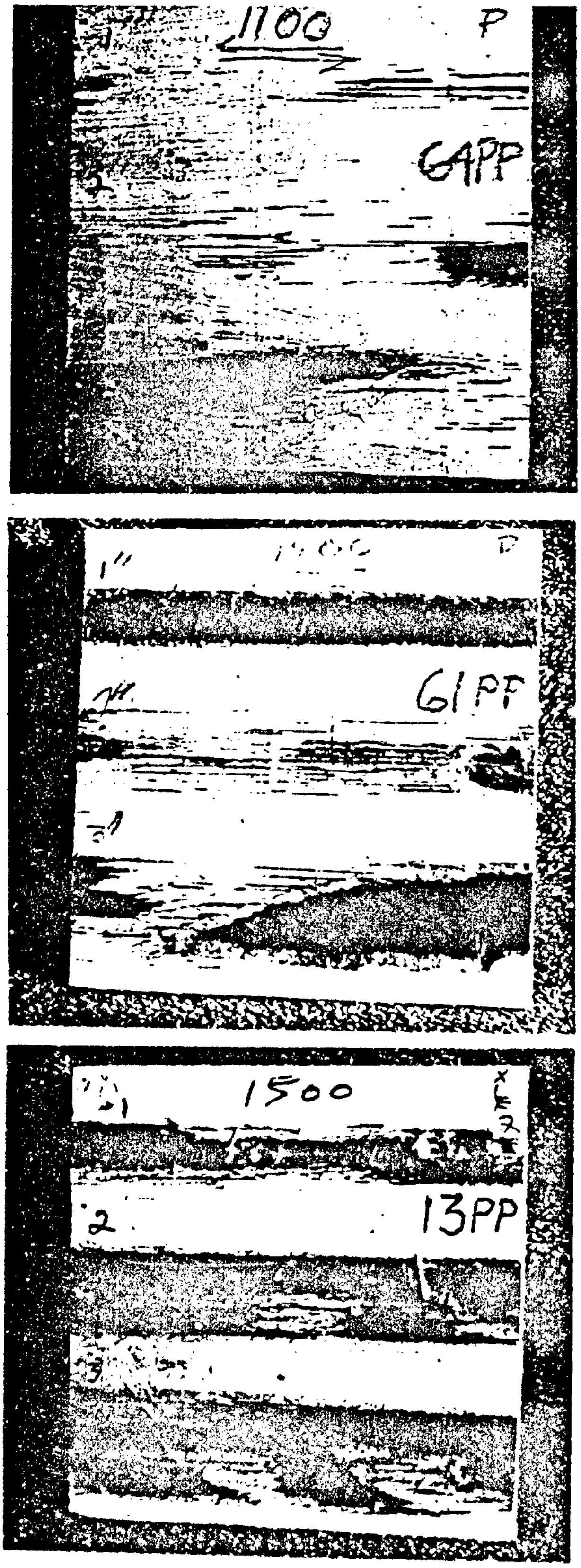
TS-304. This data subset reorganizes the results of series TS-301, TS-302, and TS-303 so as to compare the substrates separately; thus:

(1) For the pine substrate, ***Figure 26*** compares the results of Runs R-5, R-8, and R-11:

- The patterns of paint removal are similar for the three panels, despite the differences in nozzle pressure and the number of paint coats on the surface.

- The depth of wood gouging is greater at the 1500-psi nozzle pressure level than at 1100 psi; the depth of cutting is qualitatively the same in Runs R-8 and R-11, despite the thicker coating of paint in the latter test.

- The effect of wood structure variability (hardness, width, and orientation of growth rings) is apparent in these tests; cf. 2-in. separation in Run R-5 (see discussion for TS-102), and comparison between Runs R-5 (1100 psi) and R-8 (1500 psi) at 3-in. separation.

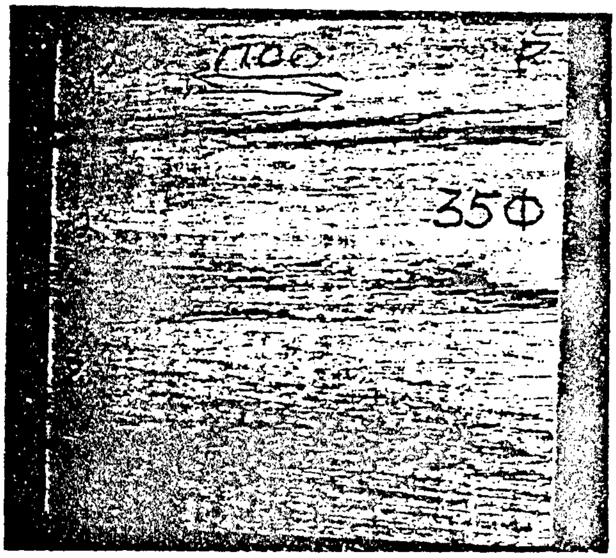


(a) **Run R-6**
1100 psi
Primer

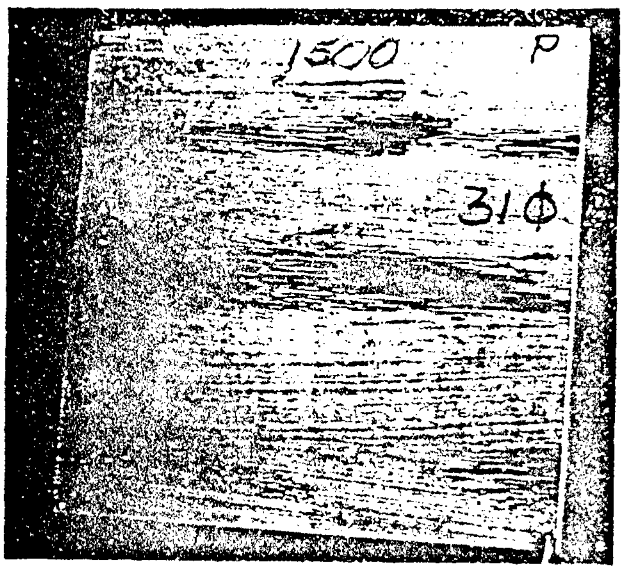
(b) **Run R-9**
1500 psi
Primer

(c) **Run R-12**
1500 psi
Primer + 2 Exterior

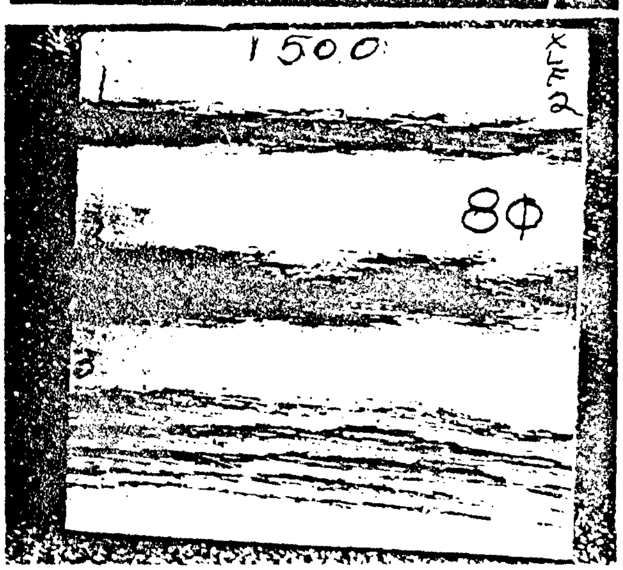
Figure 27. Fir Plywood Substrate Test Results (TS-300).



(a) **Run R-7**
1100 psi
Primer



(b) **Run R-10**
1500 psi
Primer



(c) **Run R-13**
1500 psi
Primer + 2 Exterior

Figure 28. Oak Substrate Test Results (TS-300).

(2) For the fir plywood substrate, ***Figure 27*** compares the results of Runs R-6, R-9, and R-12):

- Some grain effect (i.e., preferential removal of paint in the softer wood regions) is apparent at 1100 psi.

- Paint removal is more extensive at 1500 psi, and surface fuzzing of the wood is visible; the top ply is partially stripped at all separation levels in Run R-12.

(3) For the oak substrate, ***Figure 28*** compares the results of Runs R-7, R-10, and R-13):

- Paint removal was limited (spotty) at both pressure levels for both 1-in. and 2-in. separations.

- Paint removal was worse at 3-in. separation in Run R-10 (1500 psi) than in Run R-7 (1100 psi).

- There was no obvious wood removal, even at the higher test pressure level of 1500 psi; paint had penetrated into the minute surface cracks of the oak and was not removed by the stripping action.

Test Series 400: Effect of Hydrojet Rotation

A number of tests were essayed using rotary nozzles and rotating heads (multiple nozzles). The former were borrowed from Pittsburgh Supply and Coatings (Oak Ridge, Tennessee), and the latter was purchased from NLB Corporation. Both types of nozzles are described above under "Equipment and Facility Descriptions (Subtask 2.2)."

TS-401. The distinguishing feature of the rotary nozzle seems to be a floating cylinder at the nozzle exit that rotates freely in response to the hydrodynamic forces of the jet flow. Test conditions for the several runs, R-14 and R-15, are given in ***Table 5***. It is claimed that rotation of the jet evens the force on the surface.

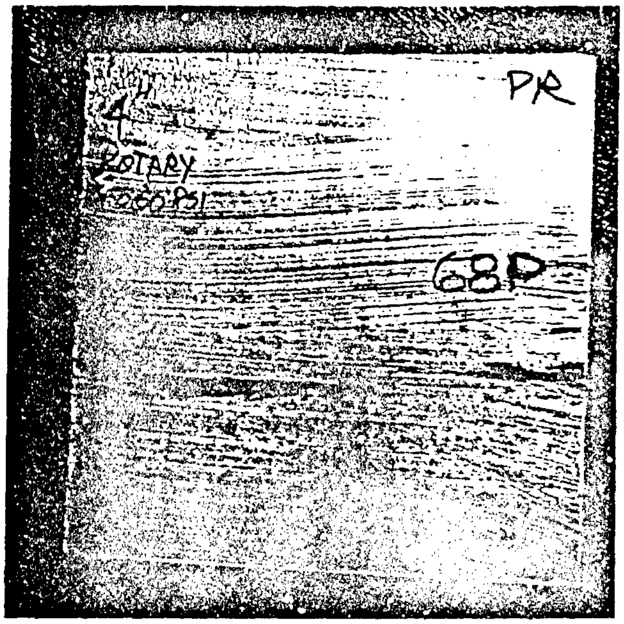
The tests were carried out using the physically larger of the two rotary nozzles; results are shown in ***Figure 29***.

- For Run R-14 (panel 68P), the nozzle-to-surface separation was 4-in.; and the nozzle pressure was 1000 psi. From visual observation, the spray did appear to rotate. Paint removal was minimal at this large separation from the painted surface, though several areas of wood gouging are visible. (***Figure 29a***)

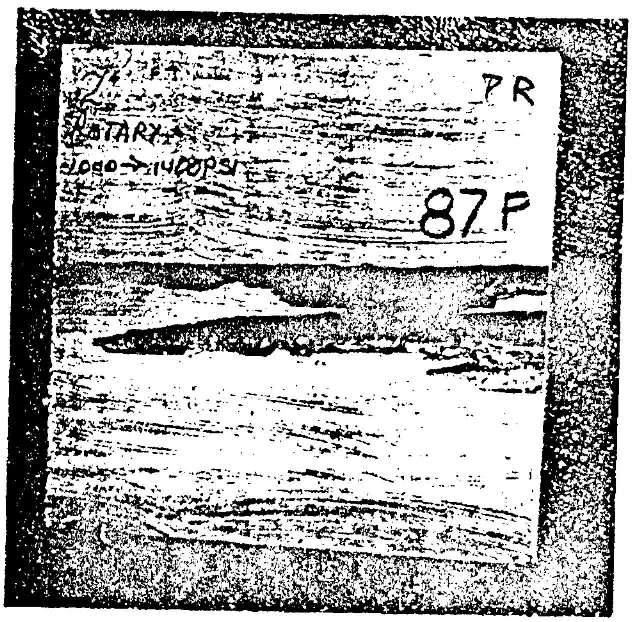
- For Run R-15 (panel 87P), the nozzle-to-surface separation was 2 in.; the nozzle pressure was varied incrementally from 1000 psi up to 1400 psi. At the lowest pressure level, paint/wood removal was similar to that observed in Run R-14. However, at 1400 psi, significant gouging of the pine substrate was observed (***Figure 29.B***)

TS-402. This test was attempted with the physically smaller of the two rotary nozzles. The nozzle did not generate a water jet at pressures up to 1500 psi; and consequently, the test was aborted.

TS-403. This series of tests was carried out with the NLB Corporation dual-nozzle rotating head pictured in ***Figure 14.B***. With the long dimension of the head oriented in the direction of the traverse, one of the nozzle sprays was approximately parallel to the traverse path; while the other was nearly perpendicular. There were no test done with both sprays having the same orientation.



(a) Run R-14, Pine
1000 psi
Primer



(b) Run R-15, Pine
1400 psi
Primer

Figure 29. Rotating Jet Test Results (TS-400).

Preliminary testing at successively higher pressures (beginning at 500 psi and advancing to 1500 psi) showed that the head did not rotate at pressures up to 1400 psi. At this latter pressure level, rotation could be initiated by manually spinning the nozzle; however, this was not sustainable. At 1500 psi, rotation was self-initiated and was sustained throughout the period of the several panel tests. The rate of rotation was not measured but was observed to be high.

Three runs (R-37 to R-39) were performed at identical test conditions (see *Table 5*) using pine, primer-coated panels. Results are shown in *Figure 30*; observations from examination of these panels after exposure are:

- In Run R-37 (panel 84P), the wood was gouged to a depth of about 0.05 in. in two separated stripes, each of about 0.6-in. width. The overall width of the impacted area was 1.6-1.7 in.; the center-to-center distance between the two nozzles is 1.2 in. One stripe of material removal extended along the full length of the panel, while the other only covered the middle region. There was no visible paint removal in the zone between the two stripes. Deep gouging was confined to the central part of each affected stripe, with some "scratches" observed in the outer regions.

- In Run R-38 (panel 105P), while the general response in this test was similar to that observed in the previous run, the distinctive difference was the lack of wood gouging. In consequence, a third test was essayed.

- In Run R-39 (panel 104P), extensive gouging was again observed. Most apparent is the disappearance of the unaffected central zone at about 1/3 of the way along the traverse from the right side of the panel. (Traverse initiated from right to left and then reversed for the second pass.) Further, there were multiple small islands on which paint remained.

Test Series 500: Effect of Paint Aging

This test series examined the effect of aging on paint removal by hydrojet. The first set of tests was done with standard test panels that were laboratory-aged by exposure to heat lamps over an extended period of time. The second set used, a field-aged specimen (a large paint chip).

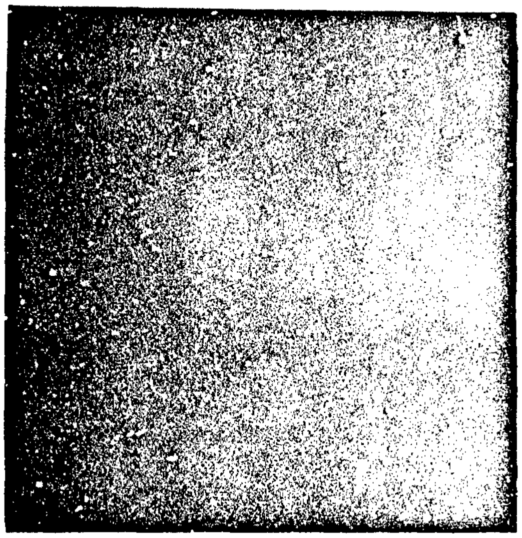
TS-501. Tests R-16 through R-21 were carried out with pine, fir plywood, and oak panels whose painted surfaces had been aged by exposure to heat lamps (see discussion under Test Procedures, Subtask 2.3). For Runs R-16 to R-18, the panels (14P, 14PP, and 9Q, respectively) were coated with primer plus two coats of exterior flat latex; for Runs R-19 to R-21, panels 9P, 9PP, and 6Q had a primer coat plus only one coat of exterior flat latex. For all specimens, exposure to heat and light was on a 24-h basis over at least a 30-day period. Undercoats were not aged in preparing any of the specimens; i.e., exposure to heat and light occurred only after the top paint coat was applied.

All runs were made at a nozzle pressure of 1500 psi with nozzle-surface separations of 1, 2, and 3 in. Test conditions are listed in *Table 5*. Results are shown in *Figures 31 and 32*. It was found that:

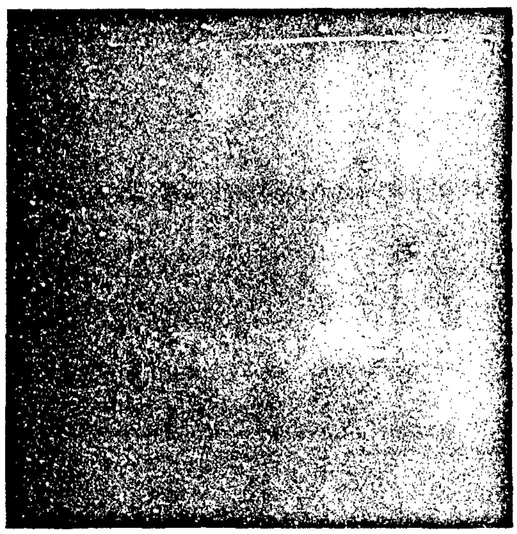
- On the pine specimens (9P vs. 14P), paint and substrate removal were more extensive (broader and deeper) on the single exterior coat specimens than on the two-coat panels.

- On the plywood specimens (9PP vs. 14PP), there was more overall ply stripping on the two-coat than on the one-coat panel; though, at 1-in. separation, gouging extended into the second ply of the one-coat panel.

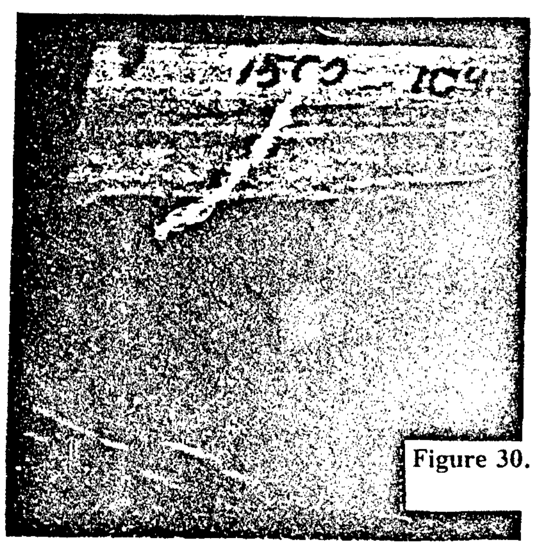
- On the oak specimens (9Q vs. 6Q), paint removal appeared greater on the two-coat panels.



(a) Run R-37, Pine
1500 psi
Primer

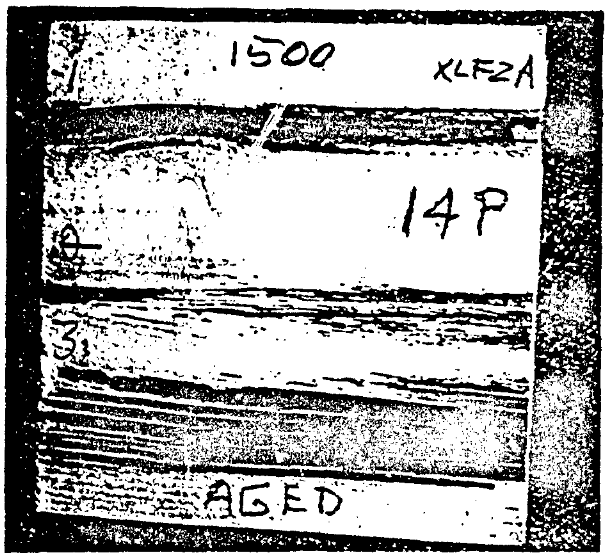


(b) Run R-38, Pine
1500 psi
Primer

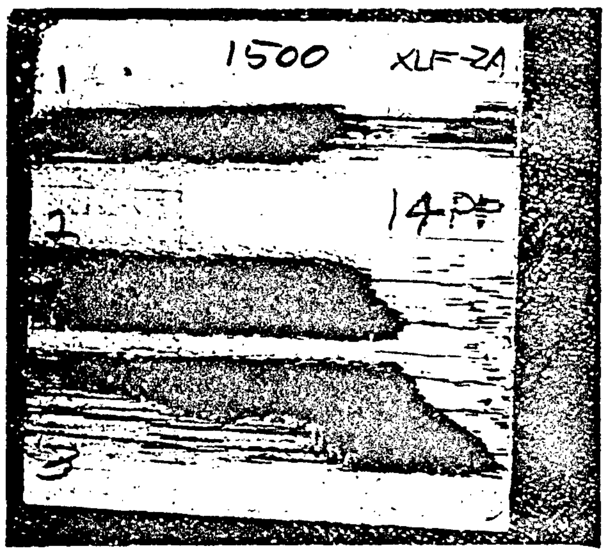


(c) Run R-39, Pine
1500 psi
Primer

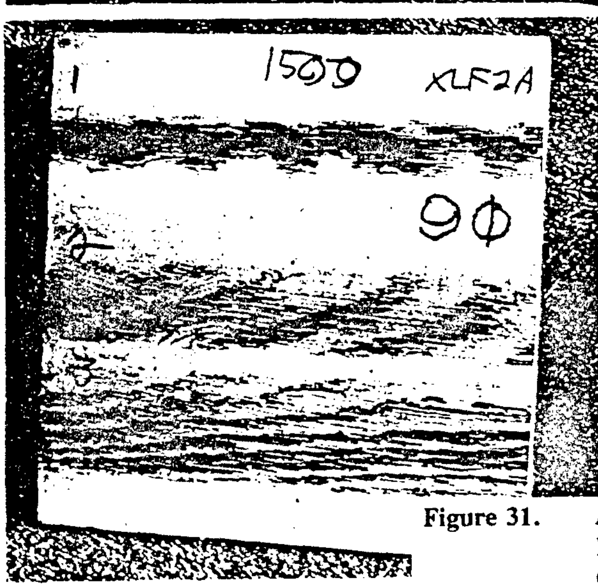
Figure 30. NLB Dual-Nozzle Rotating Head Test Results (TS-403).



(a) Run R-16
1500 psi
Pine

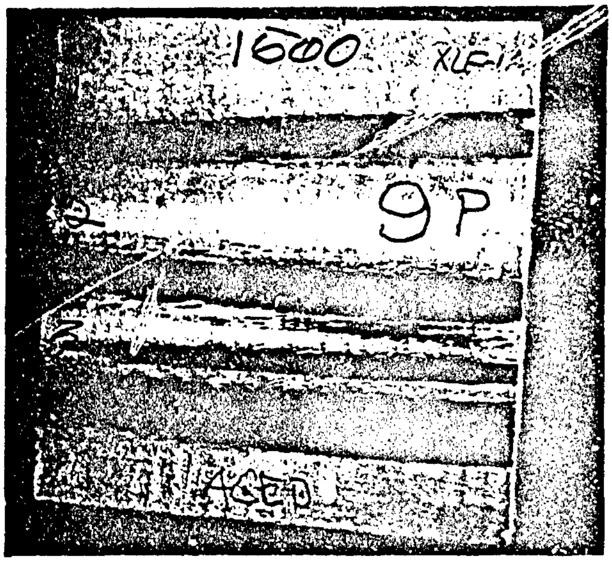


(b) Run R-17
1500 psi
Fir Plywood

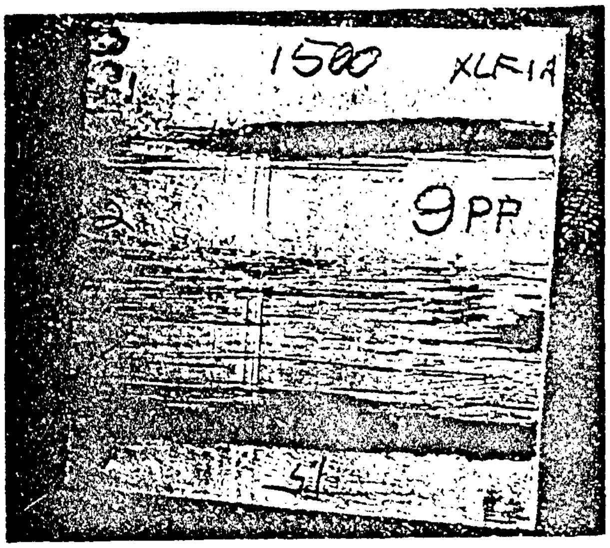


(c) Run R-18
1500 psi
Oak

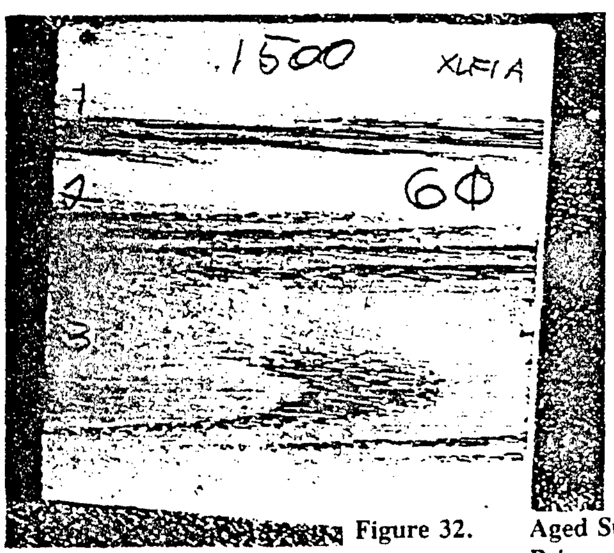
Figure 31. Aged Surface Test Results: Primer + 2 Exterior Paint Coats (TS-501).



(a) Run R-19
1500 psi
Pine



(b) Run R-20
1500 psi
Fir Plywood



(c) Run R-21
1500 psi
Oak

Figure 32. Aged Surface Test Results: Primer + 1 Exterior Paint Coat (TS-501).

- Comparison of Run R-16 (*Figure 26c*) results with Run R-11 shows more extensive paint/wood removal on the former surface. The two tests differ only in that Run R-16 was done with an unaged panel.

TS-502. Run R-36 was carried out using a paint chip obtained from an old building sited on the Fort Campbell, Kentucky, Army base. Characterization of this sample is discussed in Chapter 2 under the heading "Site Characterization (Subtask 1.2)."

The test specimen was fabricated by gluing the paint chip (about 0.055-in. thick) to the surface of test panel 47P. Test conditions (see *Table 5*) were similar to those for tests with laboratory-prepared painted surfaces with the exception that a 0-degree nozzle was used and the nozzle was not traversed across the surface (i.e., was held a fixed location). Results are shown in *Figure 33*. It was observed that:

- At nozzle pressures up to 1100 psi, there was no visible change in the appearance of the paint chip.
- At a nozzle pressure of 1300 psi, some surface cracking of the paint chip occurred.
- At a nozzle pressure of 1500 psi, there was extensive cracking of the paint chip, several pieces of the chip were "blown off" as large segments, and the jet penetrated the pine substrate to a depth of about 0.3 in.

Test Series 600: Effect of Nozzle Inclination

For these tests, Runs R-22 through R-24, the nozzle was tilted at an angle of 30 degrees from the vertical. The orientation with respect to the panel surface remained fixed regardless of the traverse direction. Other test conditions were identical to those imposed in the other parametric tests (see *Table 5*). Results are given in *Figure 34*. It was observed that:

- In Run R-22 (pine specimen 13P), significant gouging of the substrate occurred at all nozzle-surface separations (1 through 3 in.); extensive surface fuzzing was visible at 3-in. separation.
- In Run R-23 (fir plywood specimen 11PP), portions of the upper (with the grain) ply was removed at all nozzle-surface separations; there was no visible attack on the next lower (transverse grain) ply.
- In Run R-24 (oak specimen 7Q), paint removal was spotty at 3-in. separation but more uniform at 1-in.; there was some surface fuzzing.
- In comparison with Run R-11 (*Figure 26c*), a pine substrate tested at the same conditions except for nozzle inclination, wood removal was much deeper with the tilted nozzle.

Test Series 700: Effect of Pressure Level

For these tests (Runs R-25 through R-29), the nozzle pressure was increased incrementally to determine the threshold for paint removal. Test conditions are shown in *Table 5*. The tests were performed with pine panel 23P (two gloss coats over primer), and the nozzle-surface separation was held at 3 in. Results are pictured in the lower section (labeled C) of *Figure 35*. It was observed that:

- There was no paint removed at pressures up to 700 psi.
- There were a few small patches of paint stripped at 900 psi.
- Paint and soft wood were removed at a pressure level of 1100 psi.

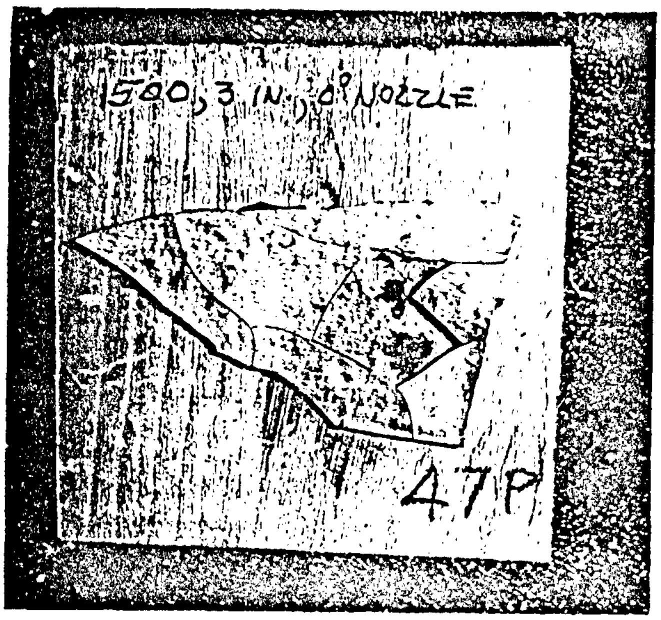
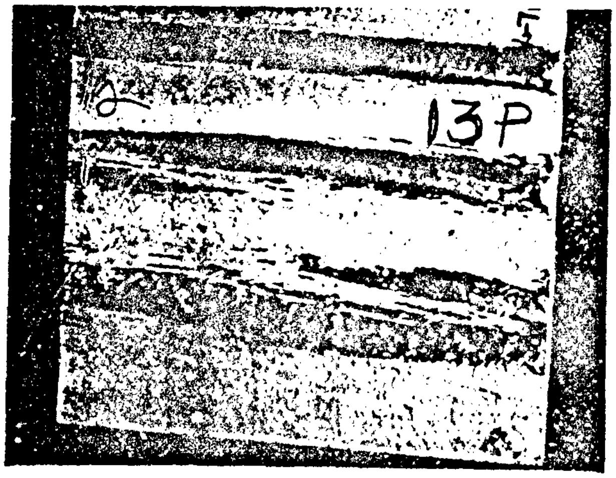
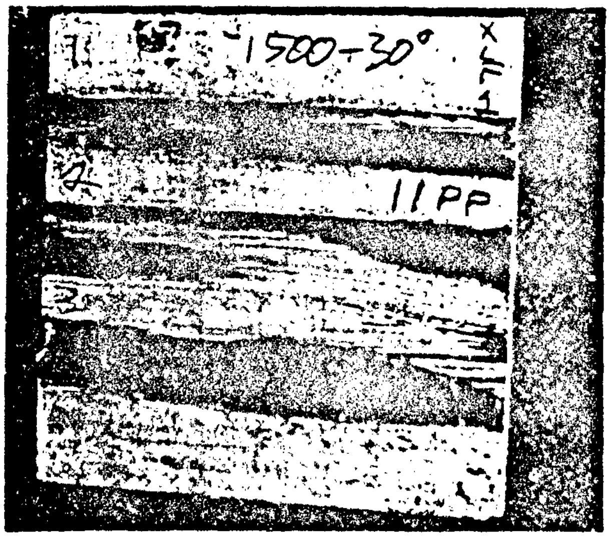


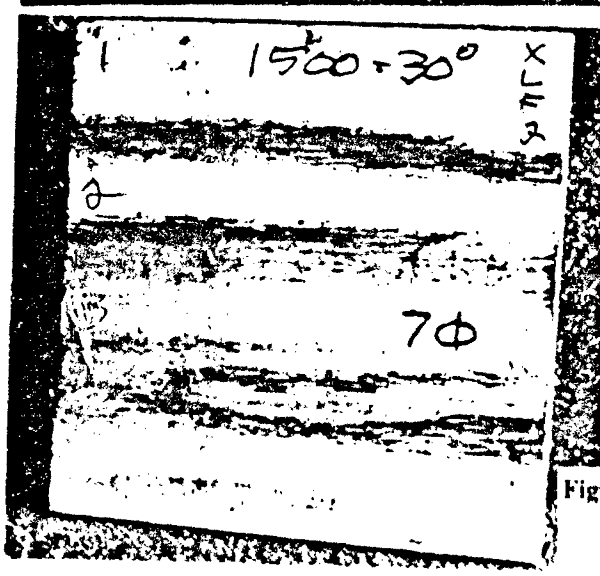
Figure 33. Fort Campbell Paint Chip Test Results (TS-502). 1100-1500 psi; 0-degree nozzle.



(a) **Run R-22**
1500 psi
Pine, Primer



(b) **Run R-23**
1500 psi
Fir Plywood, Primer



(c) **Run R-24**
1500 psi
Oak

Figure 34. Nozzle Inclination Test Results (TS-600). Nozzle 30-degrees from vertical.

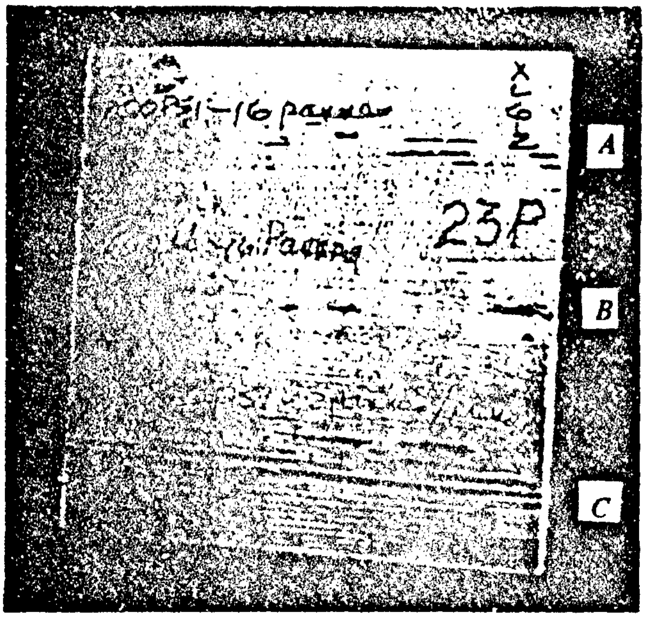


Figure 35. **Pressure Level (TS-700) and Jet Passes (TS-800) Test Results. A & B = TS-800; C = TS-700.**

These tests (Runs R-30 and R-31) examined the effect of multiple traverses at two pressure levels, 700 and 900 psi, bounding the pressure threshold for paint removal identified in Test Series 700. These tests were carried out with panel 23P at a 3-in. nozzle-surface separation; results are shown by sections A and B in ***Figure 35***. Overall test conditions were as listed in ***Table 5***.

TS-801. This series of tests was carried out at 700 psi. The results are shown by level A in ***Figure 35***; note that the appearance corresponds only to the final test in the series. It was observed through the course of the tests that:

- There was no visible paint removal for two passes (once forward and back across the surface); this is consistent with the observation in TS-700 at this pressure level.

- Several small spots of paint were removed at six passes.

- A slight increase in the amount of paint removed was observed after ten passes.

- There was minimal further increase in paint removal with 16 passes, at which point the test was concluded.

TS-802. This test series repeated the TS-801 experiment at the higher pressure level of 900 psi. As noted above, the appearance on the test panel corresponds to that of the final passes. The results are shown at level-B in ***Figure 35***; thus:

- One small spot of paint was removed at two passes; this is again consistent with the result obtained in TS-700.

- A slight increase was seen in the amount of paint removed at four passes.

- Two additional small areas of paint removal appeared at six passes.

- Two additional paint-removed spots were observed after 16 passes; previously existing spots were widened and elongated.

Test Series 900: Containment and Observation of Material Removed

This test series is described below under the heading of "Containment/Collection Shield Performance (Subtask 2.5)."

Test Series 1000: Effect of Surface Pretreatment

This test series was carried out to determine whether thermal or mechanical pretreatment of the painted surface had an affect on the extent of hydrojet paint removal for otherwise set conditions (see ***Table 5***). Testing was done at pressures below 1100 psi, in order to not obscure the results by removing paint from unaffected portions of the surface.

TS-1001. Run R-34 was performed using panel 22P on which the surface continuity of the paint film had been broken by light scratching with a wire brush. Paint removal by the brushing action was minimal. The test was carried out by repeated double passes along a single traverse line at successively higher pressure levels. Results are shown in the upper portion of ***Figure 36***; it was observed that:

- At 900 psi, paint was removed along several narrow streaks.
- At 1100 psi, paint removal was patchy with some wood gouging.

TS-1002. Run R-35 was performed using panel 21P on which the paint film was thinned by heating with a hot air jet. Heating left the test surface with a burned appearance. The test was carried out at two pressure levels with multiple passes at each pressure. Results are shown in the lower photograph of *Figure 36*. It was observed that:

- At 700 psi (level A), the initial two passes cleaned the remaining paint from two large areas with little impact on "unscorched" areas; subsequent passes (up to a total of 16) showed minimal additional effect; an unaffected area was reheated and subjected to eight additional passes with no discernible change in the amount of paint removed.

- At 900 psi (level C) with ten jet passes, paint removal was similar to that observed on unheated panels; the soft grain effect is clearly visible.

- At 1100 psi (level B) with eight passes, paint removal was in the heated areas only; there was deep gouging of the substrate.

Test Series 1100: Effect of Multiple Paint Coats

This test (Runs R-40 and R-41) examined paint removal on a surface covered with primer plus eight coats of exterior flat latex paint. The panel was air-dried for a minimum of 72 hours between coats but was not laboratory heat/light aged at any stage. An oak substrate (30Q) was used to minimize the influence of wood removal on interpretation of hydrojet stripping performance. As given in *Table 5*, the tests were carried out at 1500 psi with a 2-in. nozzle-to-surface separation. The results are shown in *Figure 37*, from which it was observed that:

- For Run R-40 (*Figure 37.A*), a nozzle having a flow of about 3 gal/min was used. The first pass removed about half of the paint layers. The second pass removed the remainder of the finish coats, leaving the primer coat and some exposed wood.

- For Run R-41 (*Figure 37.B*), the nozzle used had a flow of about 6 gal/min. The first pass left the surface appearing like the level A test after two passes. The second pass had minimal additional effect.

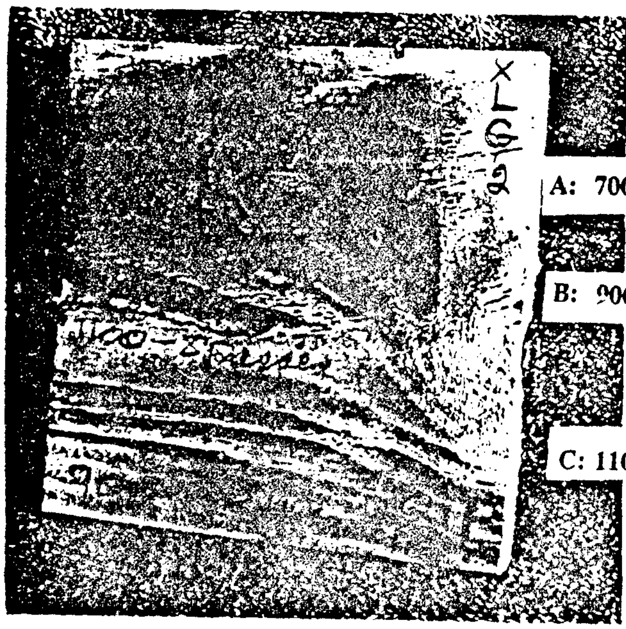
The test was not repeated with a pine substrate.

Test Series 1200: Effect of Nozzle Spray Angle

A single test (Run R-42) was performed to examine the effect of hydrojet fan spray angle on paint removal. As described in the earlier section, "Equipment/Facility Description (Subtask 2.2," commercial nozzles are available with fan spray angles of 0, 15, 25, 40, and 65 degrees. Nozzles having "tailored" spray angles can be manufactured. Cost of such nozzles will be high, and there use would not be consistent with developing a system that is convenient in cost and supply for commercial painting contractors. Based on the experience from earlier tests, this current experiment used a 0-degree nozzle; a wider angle spray (greater than 15-degree) would disperse the jet energy more diffusely over the painted surface.

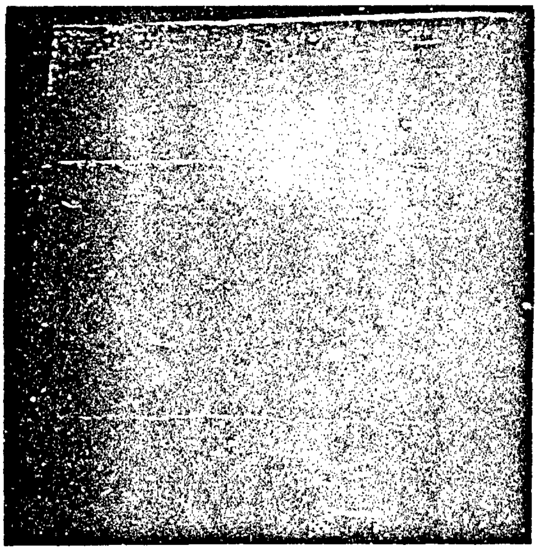
The test was carried out at two pressure levels (900 and 1500 psi) with 3-in. nozzle-surface separation. The results are shown in *Figure 38*; conditions are given in *Table 5*. It was observed that:

(a) Run R-34
700-1100 psi
Pine, Scratched



(b) Run R-35
700-1100 psi
Pine, Heated

Figure 36. Surface Pretreatment Test Results (TS-1000).



(a) Run R-40
Oak, Primer
No. 4 Nozzle

(b) Run R-41
Oak, Primer
No. 8 Nozzle

Figure 37. Multiple Paint Coat Test Results (TS-1100).

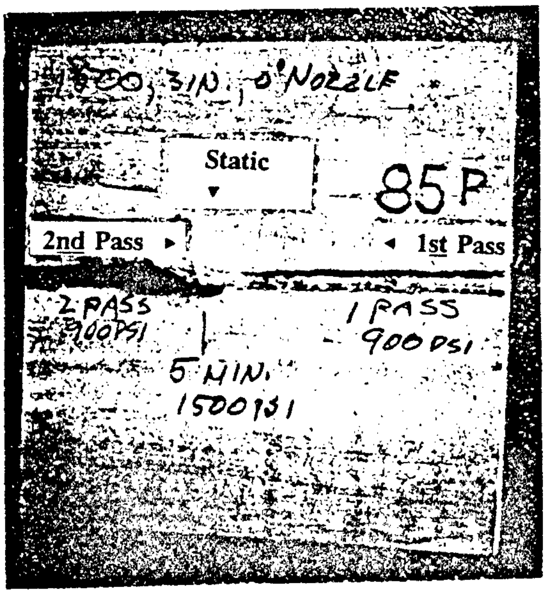


Figure 38. Nozzle Spray Angle Test Results (TS-1200).

- The first traverse (right to left in the figure) was made at 900 psi along the full length of the panel. This pass removed the primer and an additional 0.125 in. of wood in a clean stripe of about 0.375-in. width.

- The traverse direction was reversed; and the nozzle, still operating at 900 psi, was moved about one-third way along the return path of this second pass. The run was then stopped to allow convenient comparison with the first pass result. About another 0.125 in. of wood was removed without widening of the track.

- The nozzle pressure was increased to 1500 psi, and the nozzle was held in a fixed location for about 5 min. A hole of an additional 1/3-in. depth was "drilled into the wood.

Test Series 1300: Effect of Nozzle Flow Rate

This test series references the results of Runs R-40 and R-41, wherein nozzles of two different flow capabilities were used in the study of paint removal on a multi-ply coated surface. As noted in the TS-1100 discussion and in the earlier equipment descriptions, the flow associated with the 15-degree spray angle nozzle No. 4 was about 3 gal/min and with nozzle No. 8, about twice that or 6 gal/min. Test conditions are given in ***Table 5***, and results are pictured in ***Figure 37***. It was observed that paint removal in a single pass with nozzle No. 8 was equivalent to that with No.4 in two-passes.

Debris Containment/Collection Shield Performance (Subtask 2.5)

The critical element in the development of a lead-paint removal system is the ability to collect and contain the debris (paint chips and wood splinters) and water resulting from the stripping process and, hence, to reduce the amount of hazardous material requiring ultimate disposal. A containment shroud, as conceived in ***Figure 39***, was suggested in the Phase I proposal. This conceptual design would require special and costly fabrication. Thus, for the purposes of this feasibility study, a shroud was configured from a polyvinyl chloride (PVC) tee. The sketches of ***Figures 2 and 3*** and photographs of ***Figures 9 and 10***, along with the attendant discussion, provide further description of the shroud elected for use in this study. An elastic band at the open end of the tee provided an effective seal that limited the dispersal of water and debris. A flexible conduit, connected to the sidearm of the tee, was used to suck the detritus to a storage tank.

Test Series 900: Containment and Observation of Material Removed

The shroud containment concept was examined through two sets of tests. The first looked at the behavior of a prototype containment head against a smooth, flat surface; the second examined the debris resulting from the stripping activity.

TS-901. These tests were carried out to develop an efficient geometry for the seal against the work surface and to examine the shroud performance in a qualitative manner. Results were as follows:

(1) The initial test was made with a latex elastomer band stretched and clamped around the perimeter of the open end of the PVC tee. Operation of the shroud without suction showed that outward flow from the shroud was inhibited. However, when suction was applied internally, the tee was held very tightly against the work surface; and free movement of the shroud over the surface was hampered.

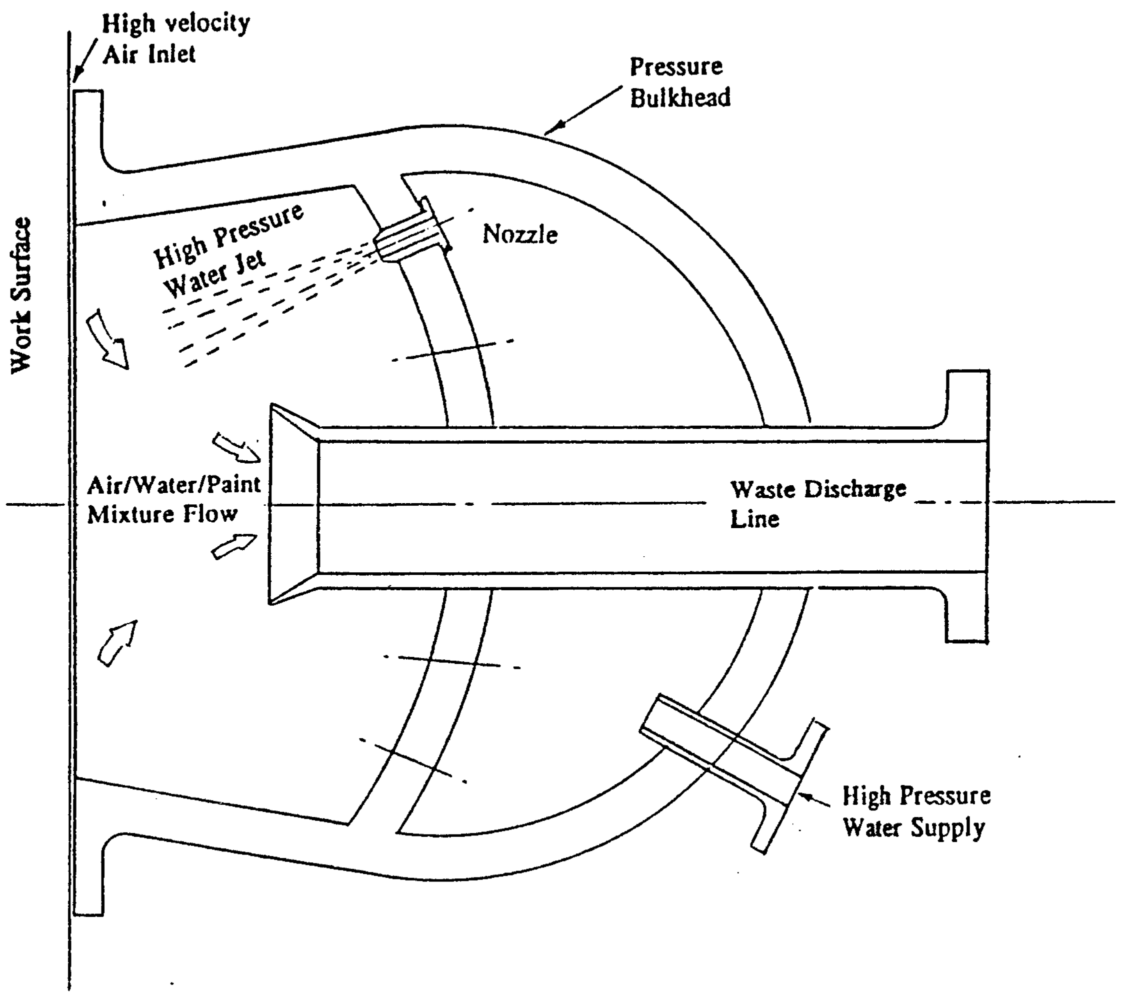


Figure 39. Schematic of Initial Concept for Containment Shroud.

(2) To remedy this situation, the PVC tee was modified by cutting 24 triangular and equally spaced notches, of about 3/8-in. base and 3/8-in. depth, into the end sealing surface. As can be seen in the photographs of ***Figures 40 and 41***, this still left a substantial amount of flat area in contact with the work surface. With suction, radially inward flow of ambient air through the notches occurred; while the seal against outward flow of water and debris remained effective. However, it was found that the ability to move the head across the surface, while improved, was still hindered.

(3) A second revision to the work surface end of the shroud inserted a PVC ring having eight legs of square cross section (~3/8-in.) equally spaced around the ring, creating a much larger air flow area (***Figure 42***). This variant worked well with regard to both movement of the shroud along the surface and retention of doth debris and water.

(4) Tests were carried out wherein the shroud was moved across an unpainted plywood surface (shown in simulated operation in ***Figure 43*** without the elastomer seal band in place). The assembled apparatus is pictured in ***Figure 44***. The results of these feasibility tests were not quantified. However, observationally, all of the water sprayed and the wood splinters formed were transferred into the tank.

TS-902. The debris from a paint removal test was examined to determine its constituents. The prototypic shroud described in the TS-901 series was not used for this purpose, since a sufficiently large painted surface was not available. Instead, the nozzle and a standard test panel were enshrouded in a sealed plastic bag to retain all of the water and debris resulting from the stripping passes. The debris was collected during the course of Run R-34 (TS-1000) with panel 22P from tests at nozzles pressures of 700 and 900 psi.

Since relatively small amounts of paint and wood were removed at these low pressures, the debris was mainly "fines". The water/debris mix collected in the plastic bag was vacuum filtered by a Bruckner funnel, and the residue on the filter paper (appearing as a set of 1/8-in. diam dots in ***Figure 45***) was examined under a microscope. Observations were as follows:

- After four passes at 700 psi, the test panel showed minor paint removal. The residue showed some paint flecks and small wood chips, translucent fibers (probably cellulose), metal shavings (probably aluminum from the test frame), and small black particles (probably coal dust).[28] The grayish color of the filter spots is accounted for this presence of coal dust.

- After four passes at 900 psi, the test panel showed a larger area of paint removal. The residue showed some larger wood chips but otherwise appeared as in the 700 psi tests. Note that the filter spots are somewhat lighter gray than observed with the debris generated at 700 psi, possibly due to "washing" of the collection bag and shroud interior by the lower pressure test.

Future Test Plans (Subtask 2.6)

Plans for future Phase II and Phase III studies are discussed in detail in Chapter 4 following.

[28]Tests using pulverized coal had been carried out in the PAI laboratory at an earlier time. Thus, the ambient air continues to have coal dust stirred up by normal laboratory activity. This dust may have been in the plastic bag used to collect the debris, perhaps within the shroud since it is stored uncovered, and possibly on the test panel since it was coated and stored inside the laboratory.

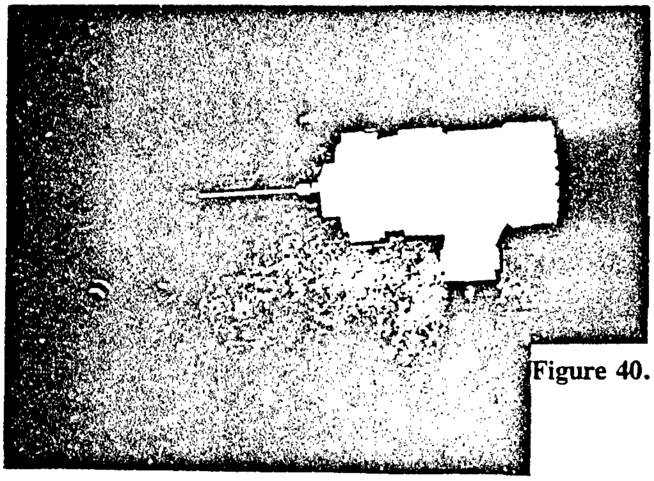


Figure 40. View of V-Notch Modified Containment Shroud. Nozzle wand and exhaust hose are shown attached.

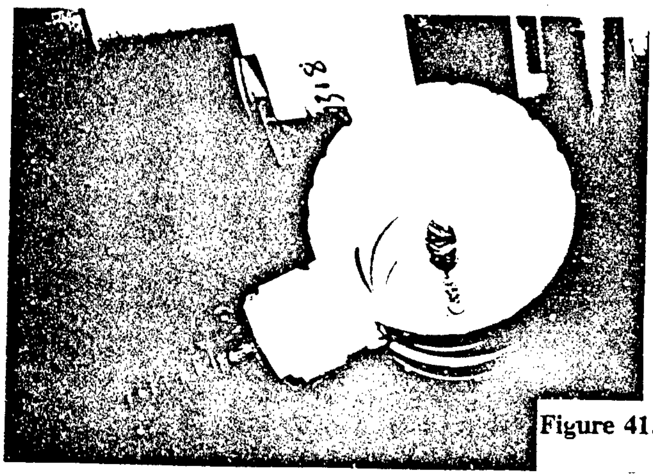


Figure 41. Interior View of V-Notch Containment Shroud.

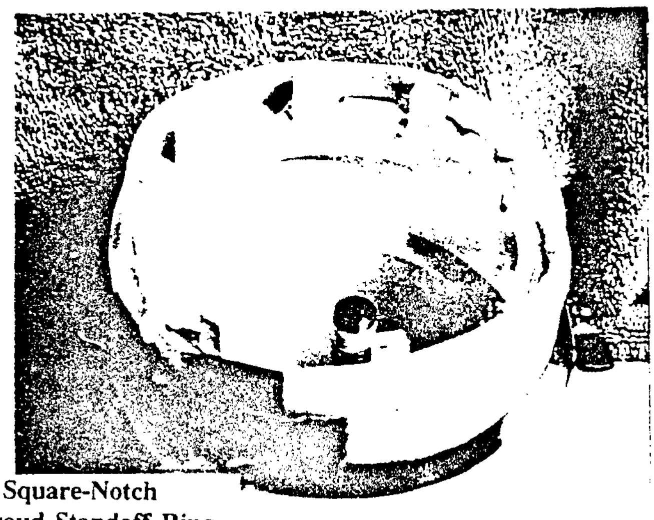


Figure 42. Closeup View of Square-Notch Containment Shroud Standoff Ring.

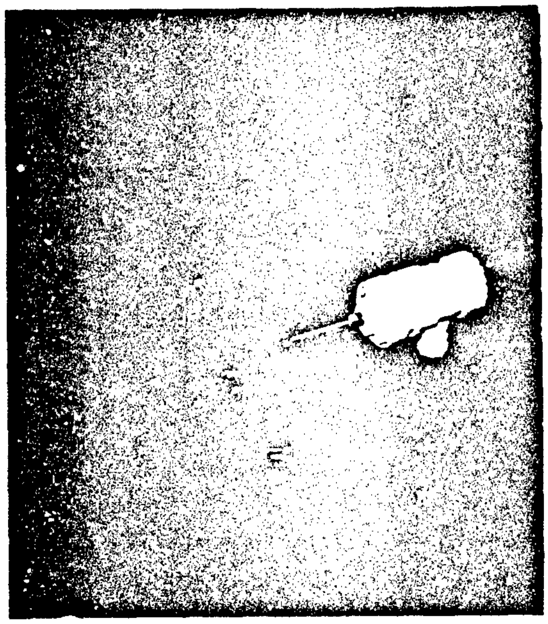


Figure 43. Simulated Operation of V-Notch Containment Shroud.

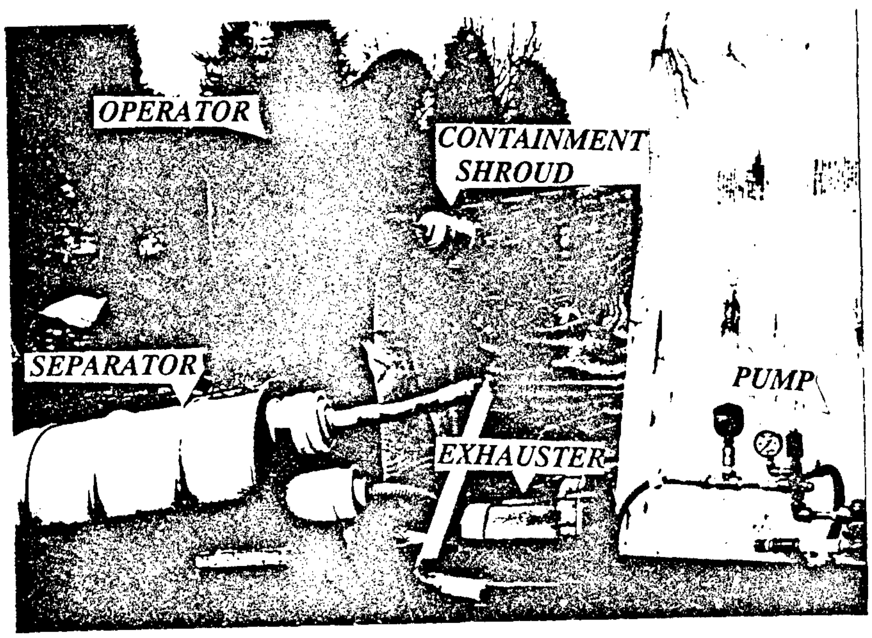


Figure 44. Laboratory-Scale Hydrojet Paint Removal Apparatus Shown Assembled.

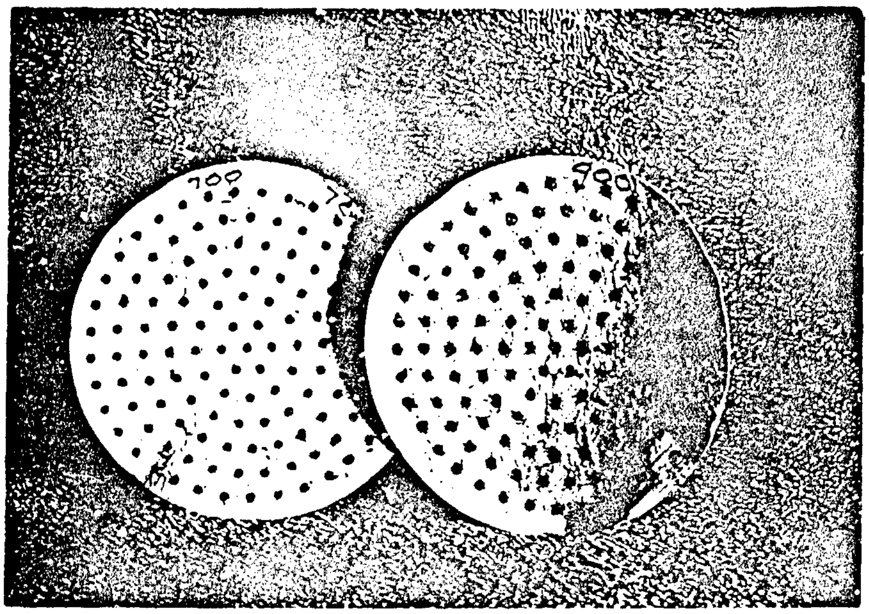


Figure 45. **Filtered Residue from Containment Tests (TS-902).**

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Summary

The experimental study carried out in this SBIR Phase I program has established the feasibility of using a confined hydraulic jet for stripping paint from wood surfaces without dispersal of the debris generated into the work ambient. This satisfies the objective of the effort to remove hazardous lead paint from wood buildings scheduled for renovation by additional of vinyl or aluminum siding or for demolition.

The effect on paint removal both of paint and wood characteristics and of hydrojet operational parameters was evaluated in a series of separate effects tests. These tests were done using small (5.5 × 5.5 in.) painted panels of pine, fir plywood, and oak mounted in a test frame controlling jet traverse across the specimen. Tests were done mainly with a 15-degree spray angle nozzle positioned perpendicular to both the test surface and the traverse direction. Stripping was more effective with traverse along the grain rather than across the grain and was more extensive on the soft wood rather than the hard wood of the grain. Both nozzle-to-surface separation and jet pressure level affected paint removal, with the area and depth ot the impacted zone increasing as the nozzle approached the surface and as the pressure was raised. Neither aging of the paint surface in the laboratory under heat lamps nor inclination of the nozzle to the surface (30-degree from the vertical) effected a change in paint removal. However, nozzle spray angle had a significant effect with the water jet from a 0-degree nozzle cutting more deeply into the wood in a narrower band.

Under the conditions of these tests, the wood substrate was removed with the paint, removal being greater with the soft pine than with the harder oak. This apparent deficiency actually enhances the effectiveness for cleaning hazardous material from the surface prior to demolition, since lead that has diffused into the wood over the building lifetime is also removed. The capability for containing the paint and wood debris in a prototypic shroud and for extracting the debris from the shroud for subsequent separation were both demonstrated.

Test Conclusions

Conclusions derived from the series of tests described in Chapter 3 are as follows:

(1) The confined hydraulic jet (hydrojet) can remove paint from wood surface, though not without removing some wood also. This is acceptable, where the purpose is to remove and concentrate the hazardous paint component prior to structure demolition or renovation (application of vinyl or aluminum siding). The latter option removes future concerns for demolition of buildings in which the lead paint had been covered.

(2) The most critical variable appears to be the character of the wood itself with respect to hardness and grain direction. Thus, stripping was more readily achieved with jet traverse along the grain rather than across the grain. Wood was gouged out more deeply in the softer portions of the growth rings. This was observed throughout the series of tests with grain orientation relative to traverse direction affecting test results. Paint removal was significantly greater on soft pine substrates than on hard oak. Under the conditions of these tests (1500 psi cap), wood was gouged deeply from pine. In contrast, paint was less easily stripped from oak, where paint remained in the porous surface cracks characteristic of oak. At higher pressures, the topmost ply of the fir plywood could be stripped.

(3) Nozzle pressure and nozzle-to-surface separation were found to be the principal operational variables; thus:

- The nozzle-pressure threshold for paint removal (i.e., the pressure level at which paint stripping is first detected) was found to be 900 psi. Increasing the nozzle pressure above this value increased the amount of paint stripped in any pass but also increased the extent of wood gouging. A nozzle pressure of 1500 psi seemed to be the most efficient level; higher pressures would probably only increase the amount of wood removed. Multiple passes at the lower pressure levels did not markedly improve the paint removal.

- The upper limit in nozzle-to-surface separation for effective paint removal was 3 in. at a nozzle pressure of 1500 psi. Increasing the separation above 3 in. diminishes the strength of the jet at the work surface and, hence, reduces paint removal. Increasing the nozzle pressure above 1500 psi recovers some of the lost effectiveness and increases the width of the paint removal stripe. However, this would require a larger pump, increasing both operating and capital costs. Decreasing the separation at a given nozzie pressure results in increased wood gouging; minimal difference was observed when the nozzle pressure was reduced along with the surface separation.

(4) A nozzle in which the jet spray rotated (claimed to even the force distribution on the surface) showed no advantage over the fixed jet in paint removal. A commercially obtained, rotating head with dual nozzles effected paint removal over a wider area and thus has potential for increasing production rate. However, paint was not removed in a central stripe along the traverse path. This unaffected region corresponds to the axis of rotation of the nozzle head, whereon a jet is not located. The impact of differences in the characteristics of the wood surface were very apparent.

(5) Buildings being considered for demolition will have received many coats of paint over the years they have been in service. This variable was studied in several tests examining the effect of multiple paint layers on the efficacy of paint removal by a hydrojet:

- The first of these tests gave an unexpected result; namely, for a fixed set of test conditions, more extensive paint removal was observed on panels with two coats than on those with one coat or on those with a primer coat only. This was particularly noticeable from comparisons with oak panels. Minute surface cracking under the jet force, possibly due to differences in adhesion and/or the coefficient of thermal expansion between the paint layers, may increase as the thickness (number of layers) of the paint film increases. This could allow penetration of the water jet beneath the paint surface and, hence, enhance "lifting" of the paint.

- A large, thick (~45 mils) paint chip taken from the siding of a building at Fort Campbell, Kentucky, showed four separate paint layers. The chip, after gluing to a test panel, exhibited cracking when exposed to a water jet from a 0-deg nozzle at 1100 psi; segments were blown from the cracked paint surface when the pressure was increased to 1500 psi. Tests were not made with the paint still adhering to the substrate, since a sample for testing in the PAI laboratory was not available.

- On laboratory-prepared, multicoated oak panels, some paint was removed on each of the two passes made at a nozzle pressure of 1500 psi; however, the paint coating was not completely stripped.

indicate a most efficient nozzle-to-surface separation of 3 in. With a 15-degree fan spray, the "cleared" stripe covered on the work surface is about 1.67-in. wide with highest removal in the central ~0.75-in. zone. This suggests a low "production rate" in the current single-jet embodiment. A nozzle generating a rotating jet, which is claimed to effect both wider coverage and more uniform force distribution on the work surface, showed little improvement in paint removal capability. A dual-nozzle, rotating head was somewhat more effective but needs further optimization.

(7) Attempts to "ease" paint removal, hence reduce substrate damage, through pretreatment of the paint surface by mechanical (abrasive) or thermal (hot air jet heating) means were not successful in these preliminary tests. While a satisfactory process could possibly be developed through additional studies, it is not apparent that any great advantage would accrue from pursuit of such an effort.

(8) The proposed technique for containing the water spray and the generated paint and wood debris and for transferring this waste to a separator/storage tank was very effective. While a separator was not tested, this device is a developed technology and will only require appropriate sizing. The use of a standard PVC tee for the shroud body seems to a cost-effective approach. Additional work is needed to optimize the configuration of the elastomer seal and standoff ring, but complications are not foreseen.

(9) Interviews with painting contractors and paint suppliers indicated that there was little experience in stripping paint from wood surfaces. There were no techniques or equipment identified that were fast, thorough, intrinsically environmentally safe, and substantially non-damaging to the surface. There was much interest in acquiring such capability.

Feasibility Issues

In Chapter 3, Subtask 2.1, four feasibility issues were raised. The experimental studies described in Subtask 2.4 addressed these issues with the following results:

(1) Can a water jet be used to strip paint from a wood surface such that all of the hazardous material (lead) is removed?

The test results show that a set of operating conditions can be established for a pine substrate that will effectively remove the paint coating. With fir plywood, the topmost ply can be stripped; while with oak, the fine surface cracking characteristic of this hard wood makes paint removal difficult. Jet movement over the surface should be in the grain direction. Additional hydrojet passes may be needed to remove paint on the harder portions of the growth rings. Substrate wood is removed along with the paint film; however, this can be advantageous in that lead (or other hazardous chemicals) that may have diffused into the wood over the lifetime of the building is also removed.

(2) Can a shroud surrounding the hydrojet prevent debris generated by the stripping action from being released into the work ambient?

The tests showed that a simple shroud constructed from a PVC tee with a properly designed standoff ring and a flexible elastomer seal would keep both water and debris within the shroud. Tipping of the shroud that might break the seal could be accommodated by a quick-acting water cutoff; this scheme was not tested in this Phase I feasibility study. The results satisfied the principal criterion that the paint be removed and collected so to as concentrate the hazardous

easily accomplished.

(3) Can the water and debris be easily transferred from the operating head (shroud) to a separator/storage tank for subsequent treatment?

Limited tests showed that there was no difficulty in transferring the water and debris without loss from the shroud to a collector tank. Centrifugal or flotation separation would use standard equipment in established processes; this was not tested in this Phase I effort. Similarly, filters and precipitators would remove fines from both air and water streams prior to release into the environment.

(4) Can a confined hydrojet paint stripping system be assembled that is simple in construction, convenient in operation, and low in cost?

Consideration of a prototypic system showed that the three given criteria can be satisfied. The system can be assembled from standard components and mounted on a wheeled trailer that can be easily moved to and around a work site. Operation and maintenance can be performed by labor of moderate skills. Capital costs, considered over a 3-year amortization period, were estimated to be reasonable in the context of both the charge for the job to the customer and the opportunity for profit to the contractor.

Considering the fifth issue raised:

(5) Can a paint stripping process be developed that leaves the surface in condition for repainting without significant refinishing but retains the advantages of the confined hydraulic jet system?

A simple hydraulic jet will remove wood substrate as paint is removed, thus leaving a surface that must be refinished prior to repainting. However, covering with vinyl or aluminum panels provides an effective after treatment.

Several alternative techniques can be conceived for removing the paint from the surface and controlling the debris. A limited thermal study showed to no advantage when used in conjunction with the hydrojet; the water jet cooled the heated surface. However, a revised hot air jet geometry with an air blower extractor, still within a shroud, could be more effective. This was not examined in this Phase I study but could be looked at as part of an expanded Phase II effort.

While the hydrojet procedure leaves the wood surface with a rough finish, the building could be covered with vinyl or aluminum siding after lead paint removal. Thus, the serviceable life of the building could be considerably extended. The principal advantage of this procedure lies in the elimination of a problem at the time of ultimate building disposal; namely, putting siding over existing lead paint would greatly increase difficulties in removing both the new and the old siding during ultimate demolition.

Recommendations

Having established the feasibility of a hazardous paint removal technique based on a confined hydraulic jet, it is recommended that a compact, portable unit be assembled and that its operation be field tested. This would constitute a Phase II effort having the following elements for feasibility verification and small-scale demonstration:

Component Optimization Studies

- Develop an optimized shroud elastomer seal and standoff ring
- Procure components and optimize operation of a debris separation and clean water recycle system
- Develop a quick-disconnect procedure to facilitate equipment changes under field conditions
- Develop or procure a multiple-nozzle head (rotating or fixed) to optimize paint removal uniformity and increase the area covered per pass
- Conceive a semi-automated system (frame and drive) to support the operating head and increase production rate
- Identify and develop operating procedures for packaging and shipping the hazardous waste generated
- Extend scoping studies to quantify the effect of the principal operating variables
- Examine alternative paint stripping techniques that are compatible (interchangeable) with the confined hydrojet and have potential for extending the utility of the process

Feasibility Verification Studies

- Procure components and assemble a portable paint stripping system for field operations
- Perform tests on wall-sized samples coated with non-hazardous paints to characterize and optimize operating procedures
- Identify and accommodate institutional issues relevant to on-site operations
- Optimize capital and operating cost factors
- Establish equipment reliability (failure rates), maintainability, and productivity characteristics

Small-Scale Demonstration

- Transfer portable paint stripping system to a designated Army base, and demonstrate performance and effectiveness in the field environment using a commercial painting firm for operations
- Modify system as indicated by testing experience
- Develop system replication costs
- Identify painting contractors, equipment manufacturers, and/or paint suppliers to share in commercialization development; and initiate cooperative agreements

A Phase III effort would include the following elements for full-scale demonstration and commercial adoption:

Cooperation and Communication

- Complete cooperative agreements with industrial and/or commercial partners
- Examine institutional issues affecting implementation, including patent and licensing rights
- Develop and implement a communications campaign to disseminate information to appropriate facility operators (military base, subsidized housing) and demolition/disposal contractors
- Identify alternative applications where dispersal of surface contaminants or cleaning solutions into the ambient is undesirable; e.g, interior surface cleaning in manufacturing plants, low-level radiation contamination on surfaces and equipment, and building exterior surface cleaning

Demonstration and Marketing

- Work with partners to construct a commercial system
- Demonstrate performance under full-scale conditions; obtain firm capital and operating cost data; replicate tests to confirm performance
- Develop marketing strategy; license technology or setup manufacturing capability

Potential Applications

While development of this paint removal device/process is directed primarily to the end use of minimization of hazardous waste from the demolition or renovation of older wooden structures on military bases, there does exist potential in related applications:

- Inner/central city buildings provide low-cost housing for a significant portion of our population. This applies in small towns, as well as in large cities. All of these old buildings have multiple coats of lead-based paints on both exterior and interior surfaces. The health hazard relative to child mental development is clearly present. At the same time, landlords cannot afford the costs of current procedures for "cleaning up" this hazard. The proposed system could provide an efficient means that is well within the budgets of the owners and whose use is within the capability of moderately unskilled labor.
- Operations in lead processing industries (e.g., primary as in smelting and secondary as in battery cracking) result in substantial contamination of building interior surfaces. Standard cleanup procedures (e.g., high-pressure hosing) could lead to substantial environmental contamination through discharge of lead compounds to storm drains and generation of lead-bearing aerosols from water splash. The confined hydraulic jet, while being a more tedious process, would occasion "cleaner" surfaces under less hazardous working conditions.
- Extension of this concept to the removal of other surface contamination is also feasible. Combination with absorbent or chemical precipitation procedures could effectively concentrate the hazardous materials. Again, the process should be both capital and operating cost effective.

METRIC CONVERSION TABLE

	To Convert From	To	Multiply By
Area	ft^2	m^2	9.290E-02
Cost	\$/ton	\$/kg	1.100E-03
	\$/ft^2	\$/m^2	1.076E+01
Flow	gal/min (gpm)	m^3/h	2.272E-01
	ft^3/min (cfm)	m^3/h	1.699E+00
Length	in	cm	2.54 E+00
	in	m	2.54 E-02
Pressure	lb_f/in^2 (psi)	megapascal (MPa)	6.898E-03
Temperature	°F (T_f)	°C (T_c)	$T_c = (T_F - 32)/1.8$
Volume	gal	m^3	3.785E-03
	ft^3	m^3	2.832E-02
Weight	lb_m	kg	4.585E-01